# Searches for electroweak production of supersymmetric gauginos and sleptons and R-parity violating and long-lived signatures with the ATLAS detector

Ruo yu Shang

University of Illinois at Urbana-Champaign

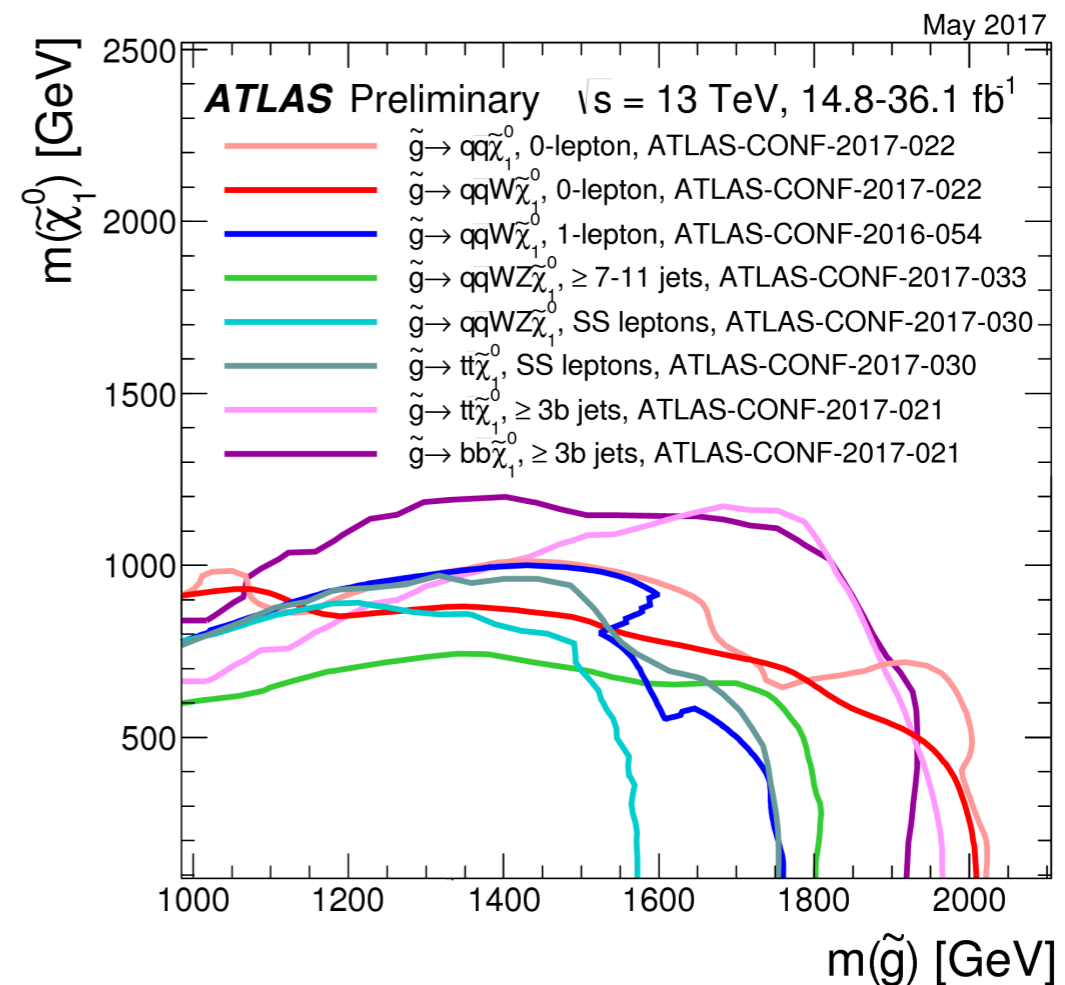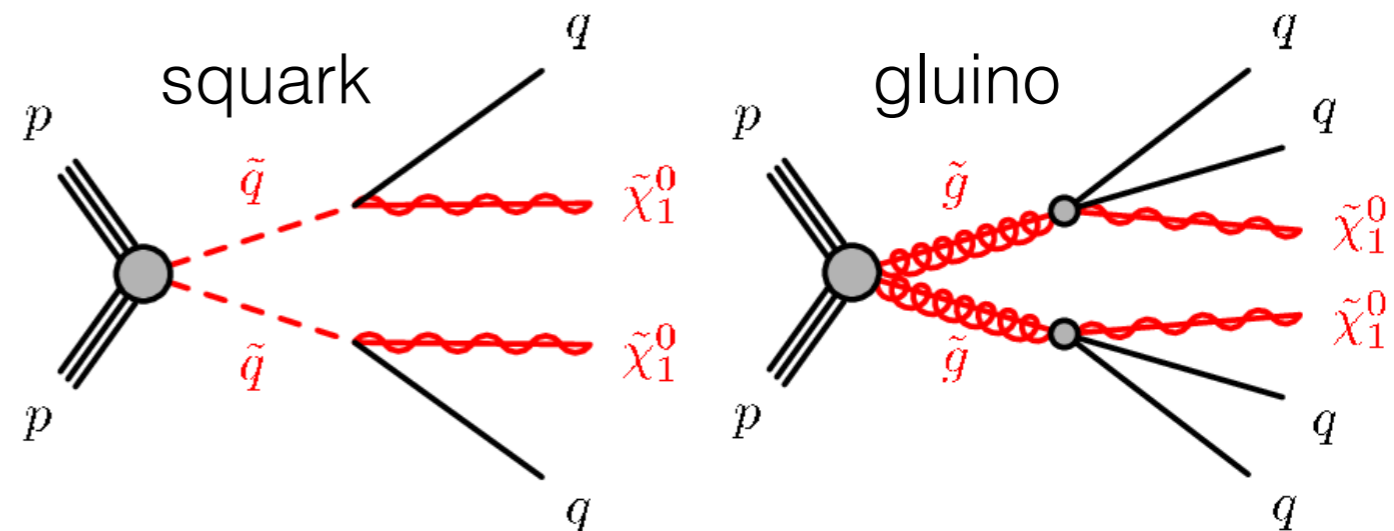(for the ATLAS collaboration)

Supersymmetry (SUSY)

- Standard model does not answer: What is dark matter? Why is the mass of Higgs not at Planck scale?

- SUSY states the existence of the **super partners** whose **spin** differing by 1/2.

- A solution to cancel the quantum corrections and restore the **Higgs mass**.

- Also provides a potential candidate to **dark matter** with a stable WIMP!
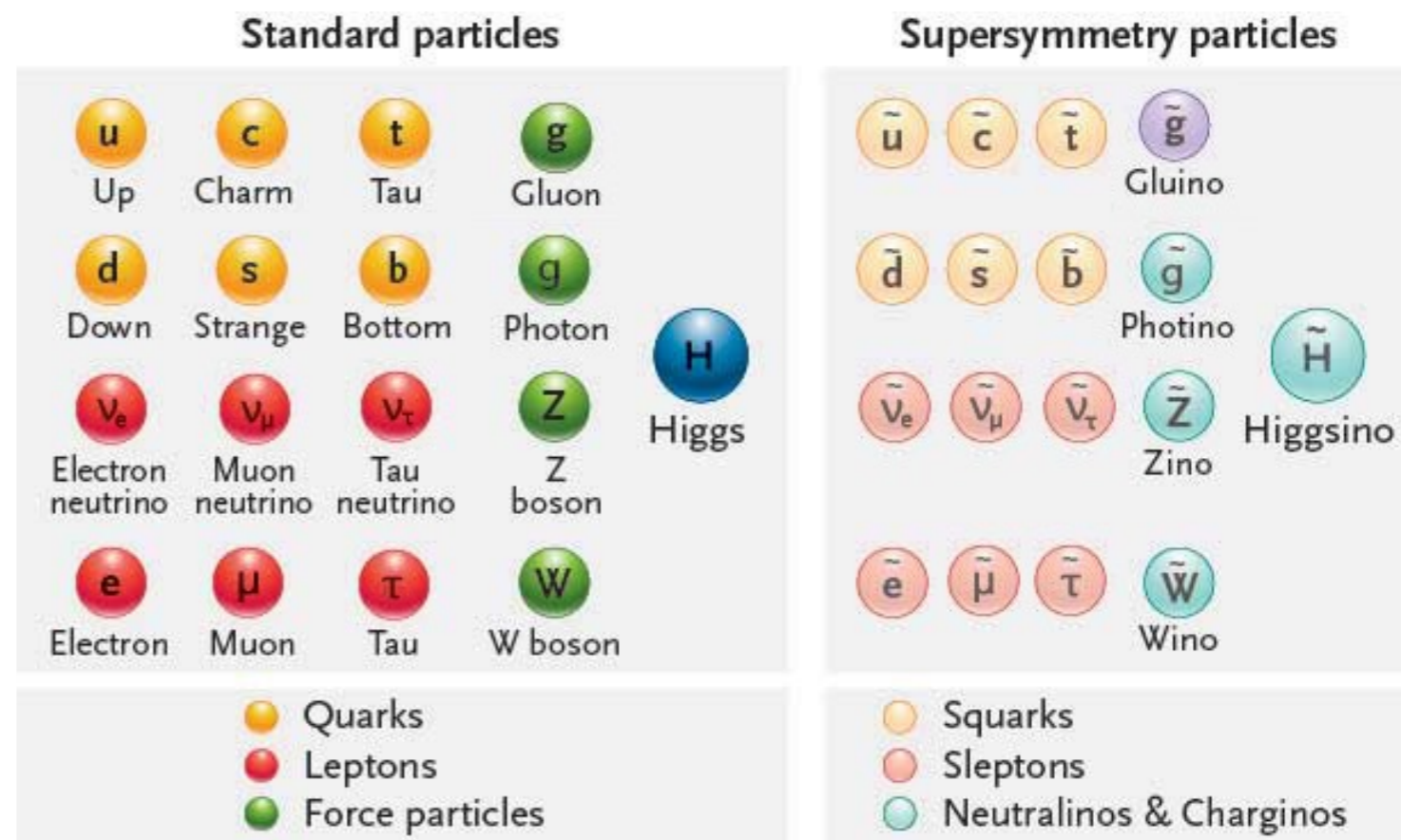
Search for SUSY at LHC

1. Gluino, stop, higgsino are the most important ones to the problem of Higgs mass.

2. Standard search for gluino/squark (top-right plots) usually includes

   - large jet multiplicity

   - missing energy $\not{E}_T$ carried away by lightest SUSY particle (LSP)

   - See next talk by Dr. Vakhtang TSISKARIDZE.

3. Dozens of analyses have extensively excluded gluino mass up to ~2 TeV. Still no sign of SUSY.

4. What are we missing?

squark

p q

$\tilde{q}$ $\tilde{\chi}_1^0$

p q $\tilde{q}$ $\tilde{\chi}_1^0$

gluino

p q q

$\tilde{g}$ $\tilde{\chi}_1^0$

$\tilde{g}$ $\tilde{\chi}_1^0$

p q q

May 2017

ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 14.8-36.1 fb^{-1}

$\tilde{g} \to qq\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2017-022	
$\tilde{g} \to qqW\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2017-022	
$\tilde{g} \to qqW\tilde{\chi}_1^0$, 1-lepton, ATLAS-CONF-2016-054	
$\tilde{g} \to qqWZ\tilde{\chi}_1^0$, ≥ 7-11 jets, ATLAS-CONF-2017-033	
$\tilde{g} \to qqWZ\tilde{\chi}_1^0$, SS leptons, ATLAS-CONF-2017-030	
$\tilde{g} \to tt\tilde{\chi}_1^0$, SS leptons, ATLAS-CONF-2017-030	
$\tilde{g} \to tt\tilde{\chi}_1^0$, ≥ 3b jets, ATLAS-CONF-2017-021	
$\tilde{g} \to bb\tilde{\chi}_1^0$, ≥ 3b jets, ATLAS-CONF-2017-021	

$m(\tilde{\chi}_1^0)$ [GeV]

$m(\tilde{g})$ [GeV]

This talk

- Alternative searches to probe supersymmetry.

    1. Search for electroweak SUSY

    2. Search for R-parity violating SUSY.

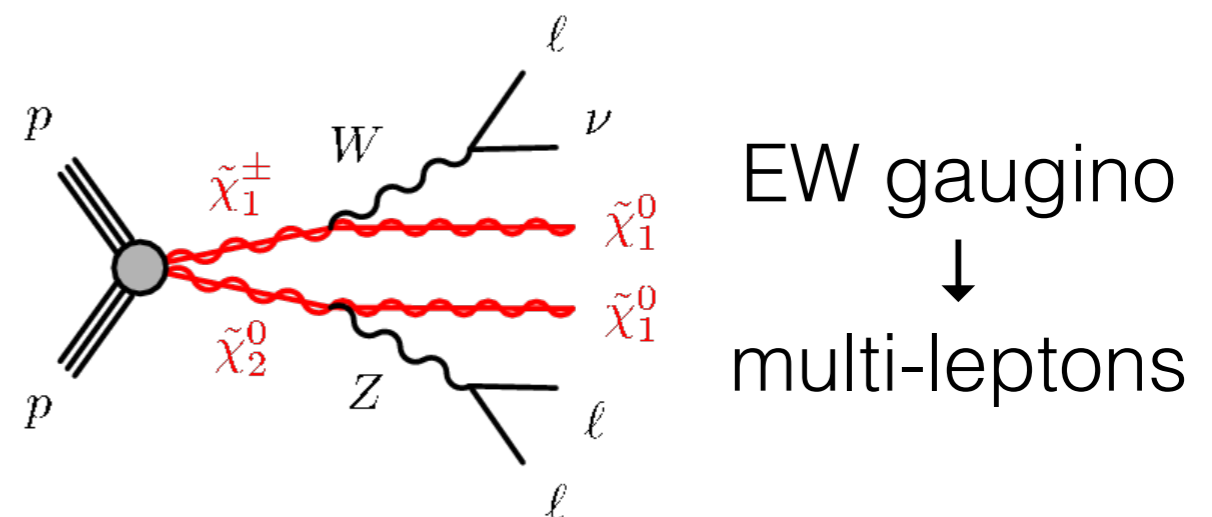   3. Search for long-lived particles.

Search for electroweak SUSY

1. Perhaps gluino mass is beyond LHC energy scale.

2. Let's try to find gauginos!

3. For electroweak productions we look for

   - leptons (e/μ/τ) from chargino/neutralino decay.
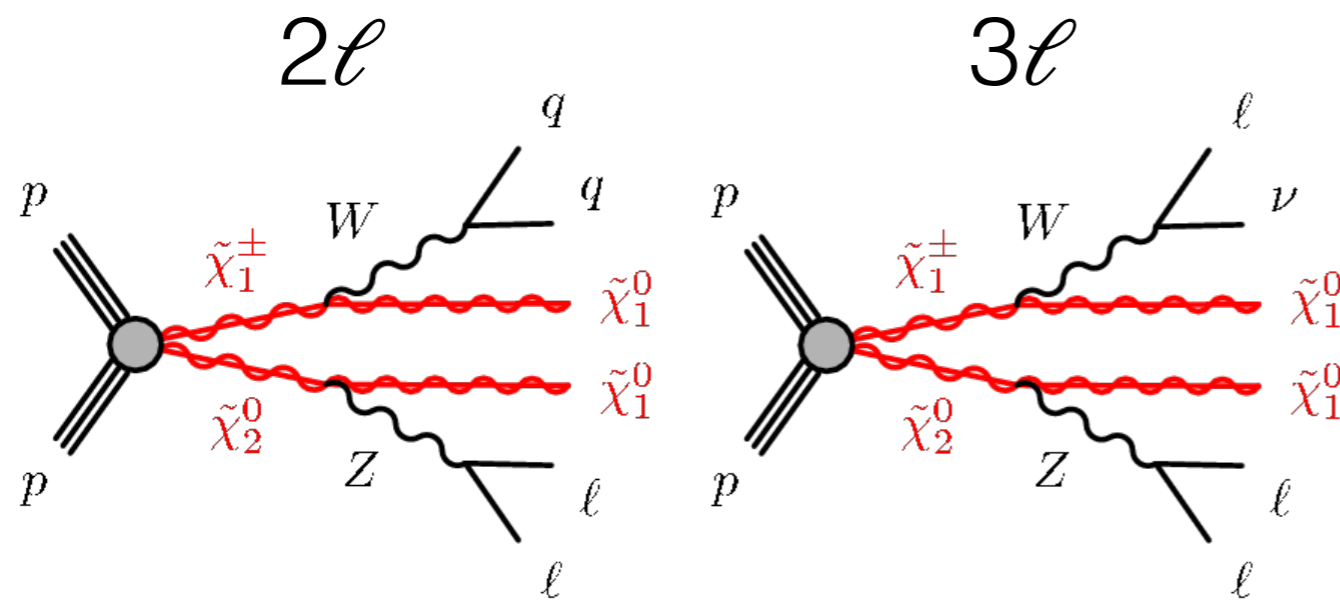
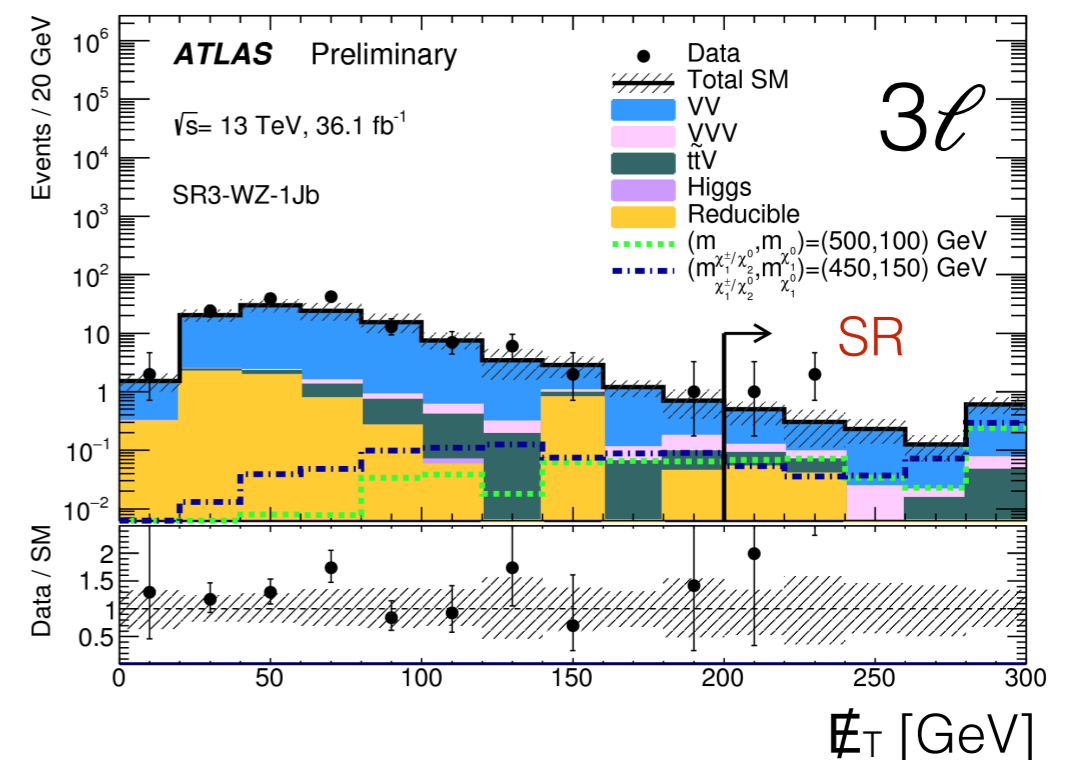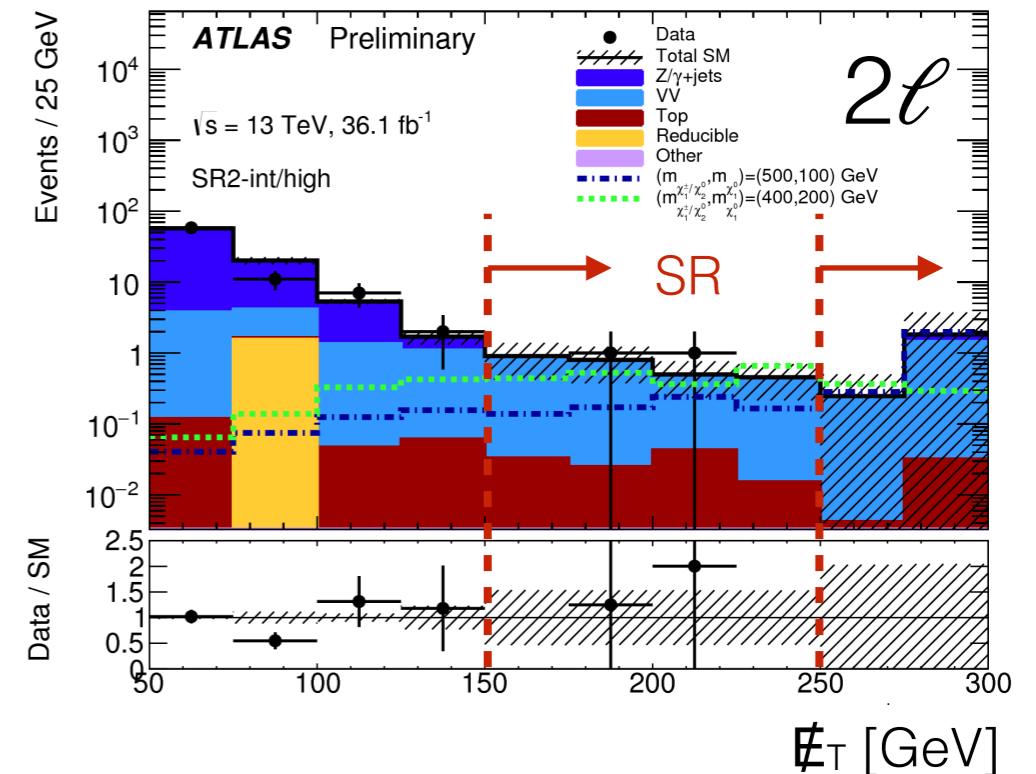   - $E\!\!\!/_T$ carried away by LSP.

Look for strong interaction

gluino
↓
multi-jets
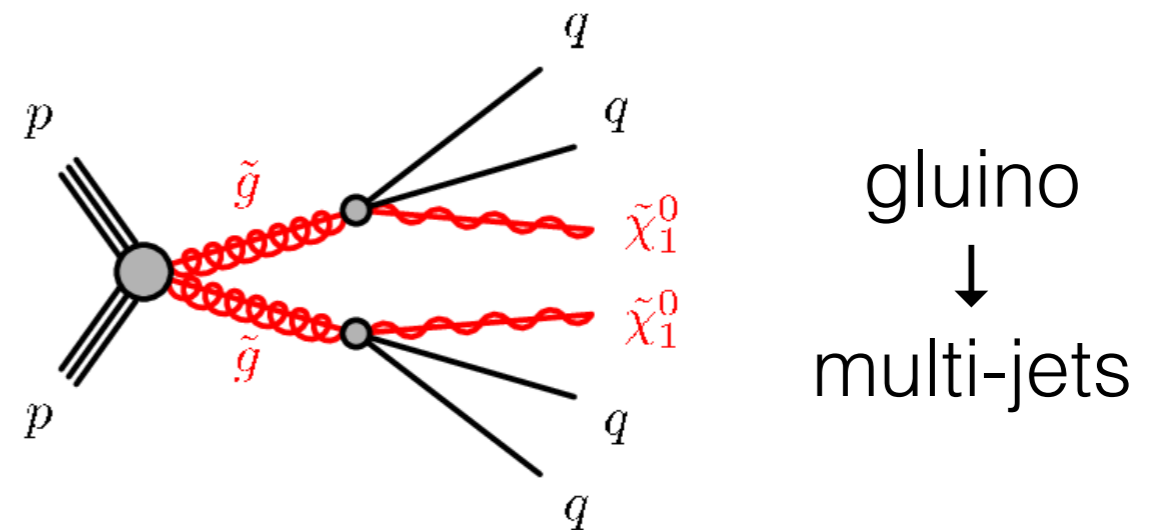
Look for electroweak interaction

EW gaugino
↓
multi-leptons

Neutralino/chargino via WZ decay

2ℓ

3ℓ

- Models assume gauginos decay to **W/Z** + LSP.

- Look for $Z \to \ell\ell$ ($W \to jj$) with large $\not{E}_T$.

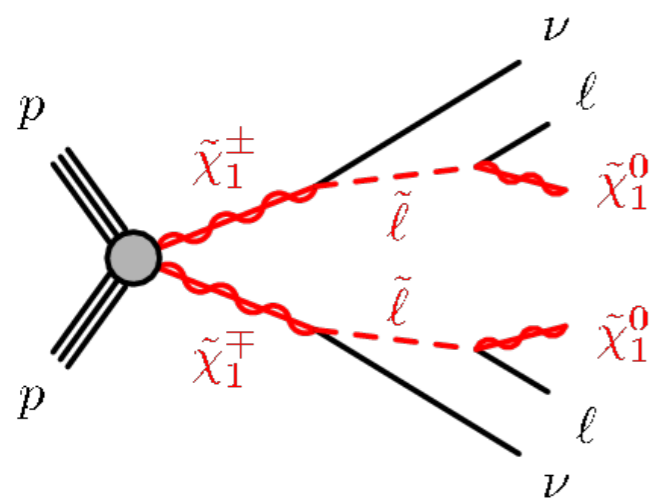- Observed data yields are consistent with background predictions.

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Neutralino/chargino via WZ decay

- Interpret the results as "simplified model" (also for CMS results):

  - masses of neutralino/chargino are the only parameters

  - other superpartners are decoupled

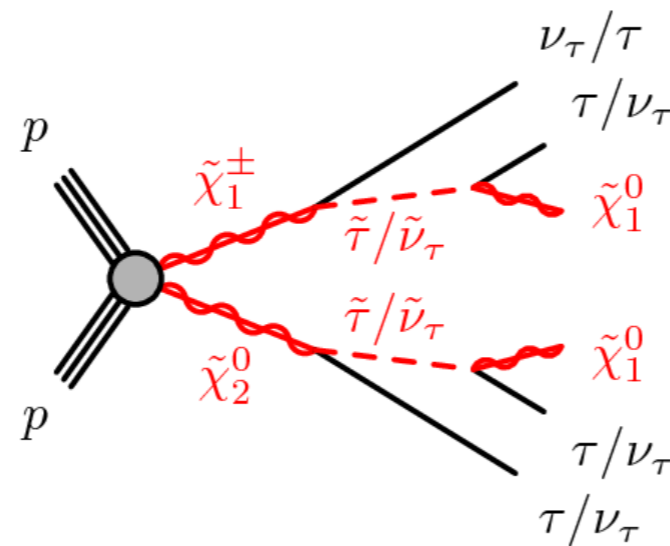- Exclude gaugino mass up to 580 GeV based on the consistency between observation and background estimate.

$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to W (\to qq) \tilde{\chi}_1^0 Z (\to l^+l^-) \tilde{\chi}_1^0$

ATLAS Preliminary

$\sqrt{s}=13$ TeV, 36.1 fb^{-1}

Observed limit

Expected limit ($\pm 1\,\sigma_{exp}$)

ATLAS 8 TeV arXiv:1403.5294

$\chi_1^\pm \chi_2^0 \to 2\ell$ via WZ

Excluded!

$m_{\tilde{\chi}_1^0}$ [GeV]

$m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^\pm}$ [GeV]
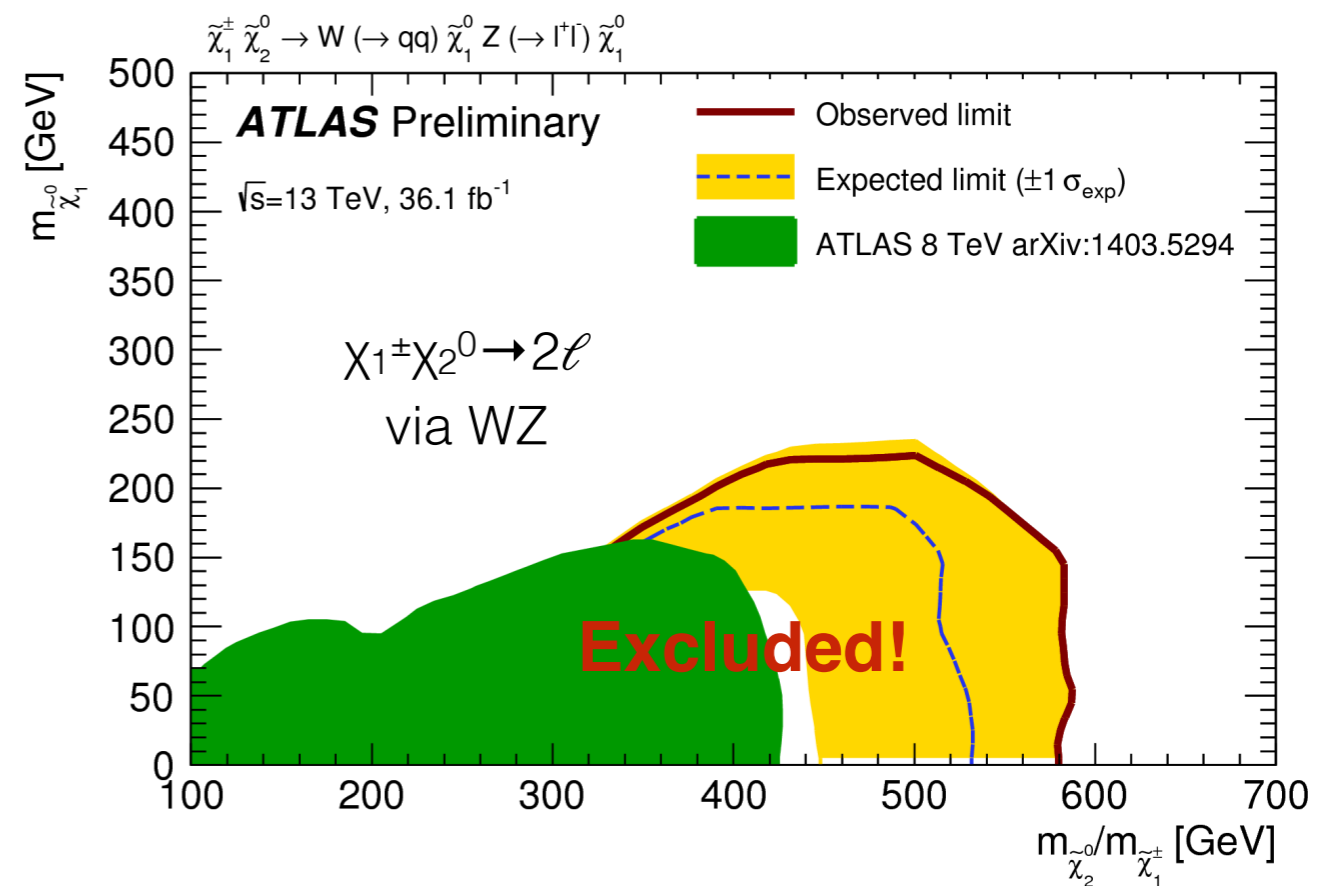
Neutralino/chargino via slepton decay

decay to e/μ   decay to τ
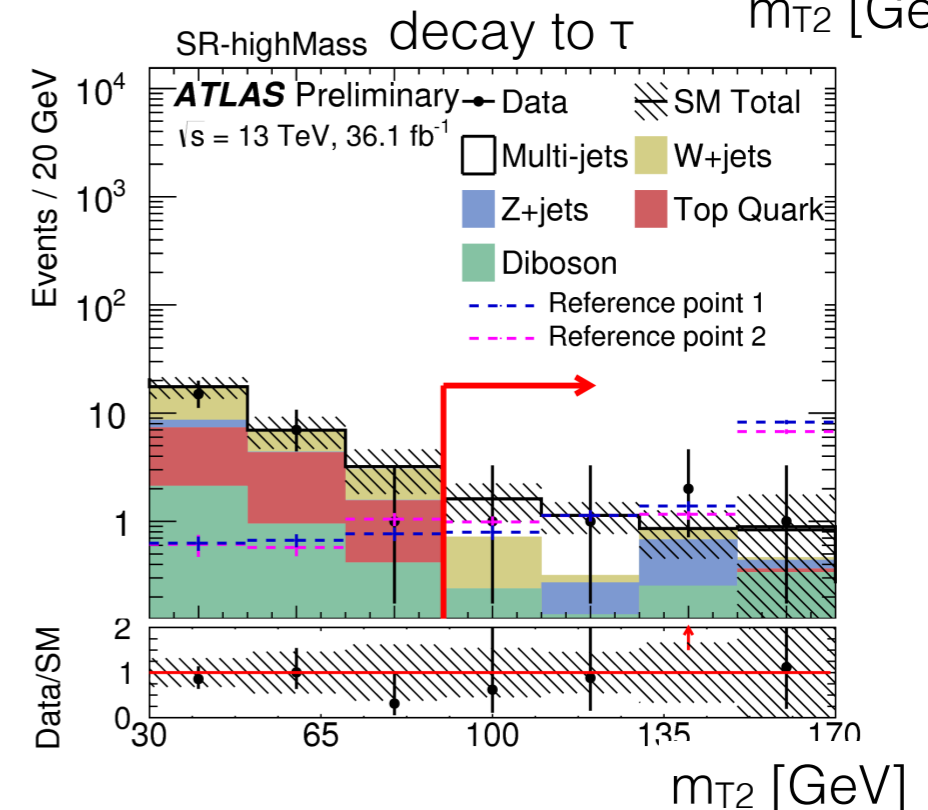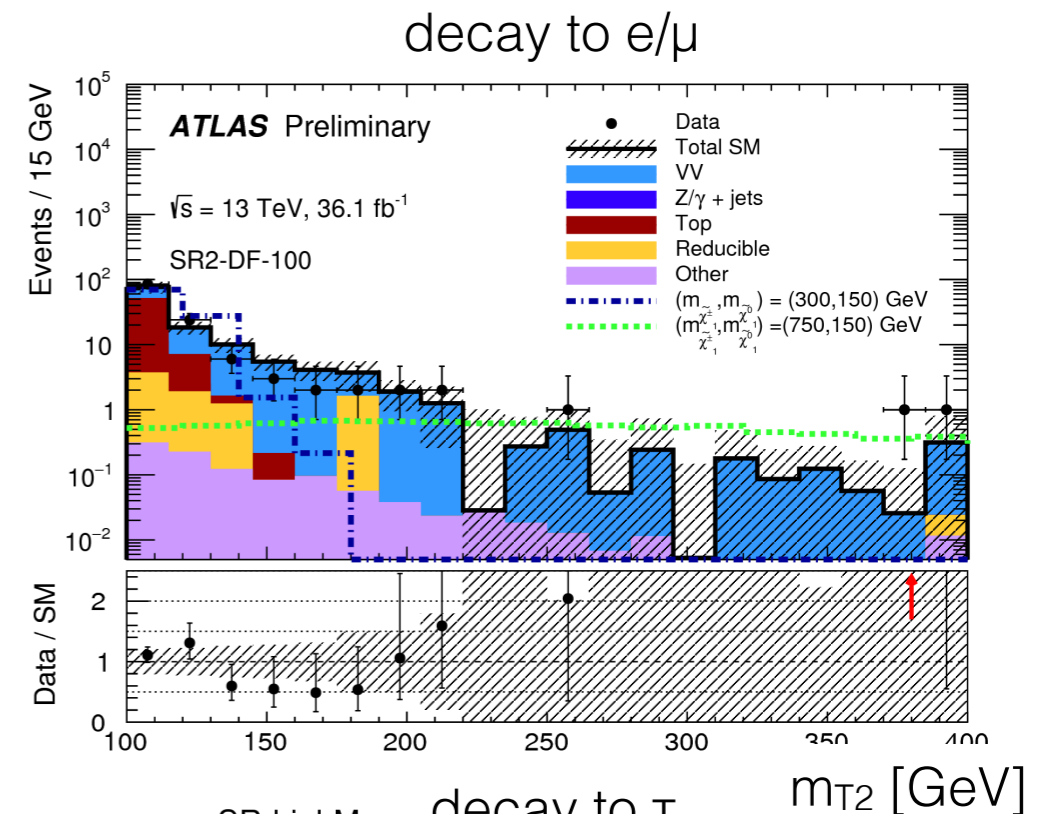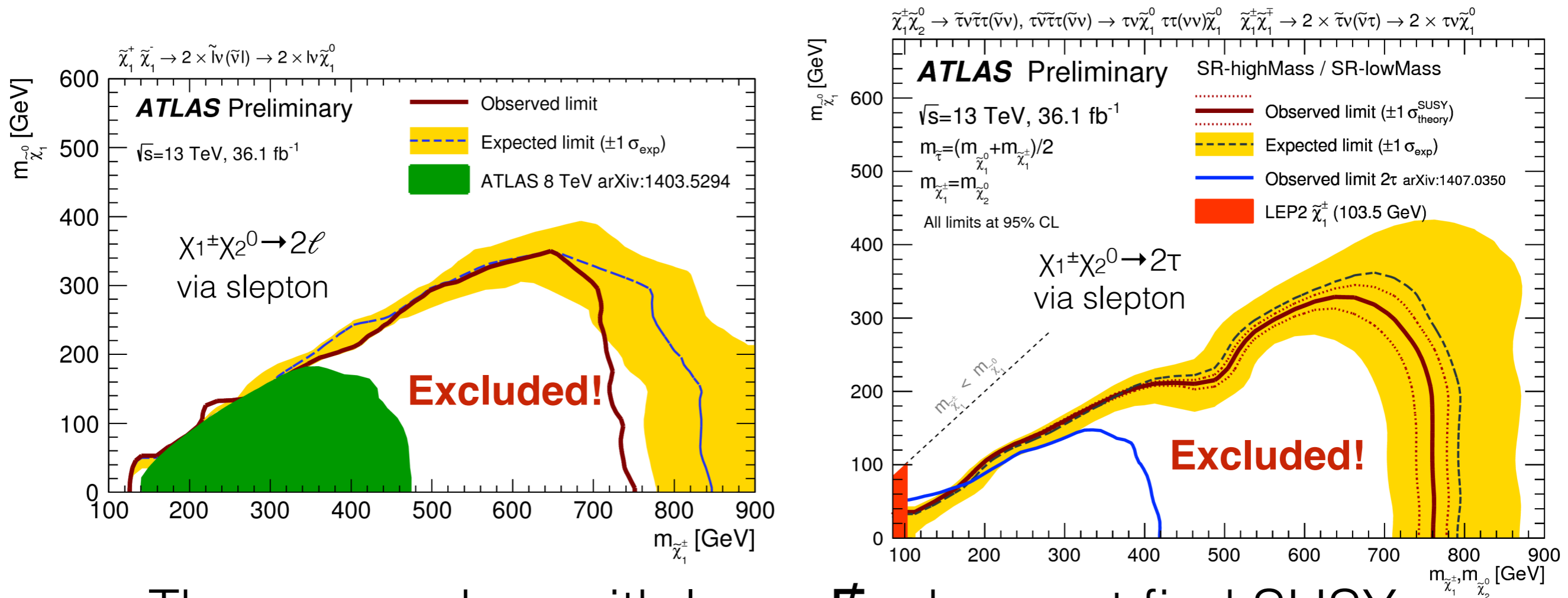

decay to e/μ

decay to τ

- Gauginos decay to LSP through **slepton**.

- Look for leptons inconsistent with Z decay

- Use m_{T2} (transverse mass built from ℓ and $\not{E}_T$) to reject backgrounds with two W→ℓν decays.

Neutralino/chargino via slepton decay

- Exclude gaugino mass up to 750 GeV based on the consistency between observation and background estimate.

These searches with large E_T does not find SUSY.
What if LSP can decay and does not produce large E_T?

Search for RPV SUSY

1. SUSY allows the violation of lepton & baryon number conservation. This leads to short life of protons.

2. R-parity conservation is a way to preserve proton lifetime (also provides a nice DM candidate).

3. There are other ways too (RPV SUSY)

   - only allow baryon # violation

   - only allow lepton # violation

4. Search strategy includes:

   - high final-state multiplicity

   - does **not require large** $\not{E}_T$

RPC, stable LSP, $\not{E}_T$

RPV, LSP decays
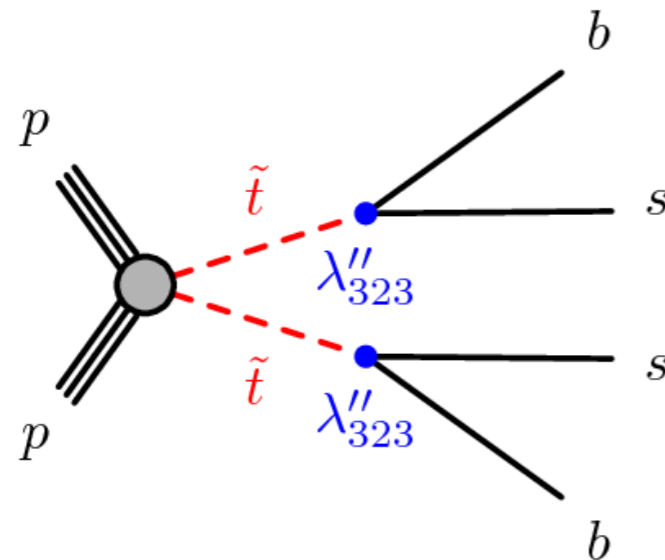
# Search for RPV with 1ℓ+jets
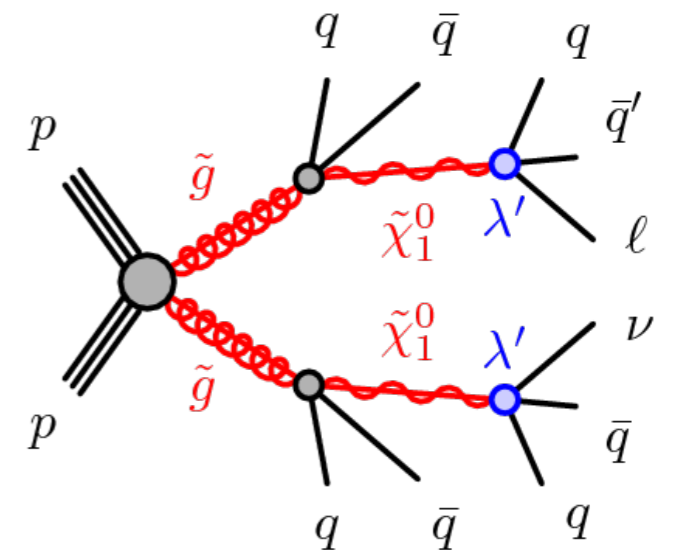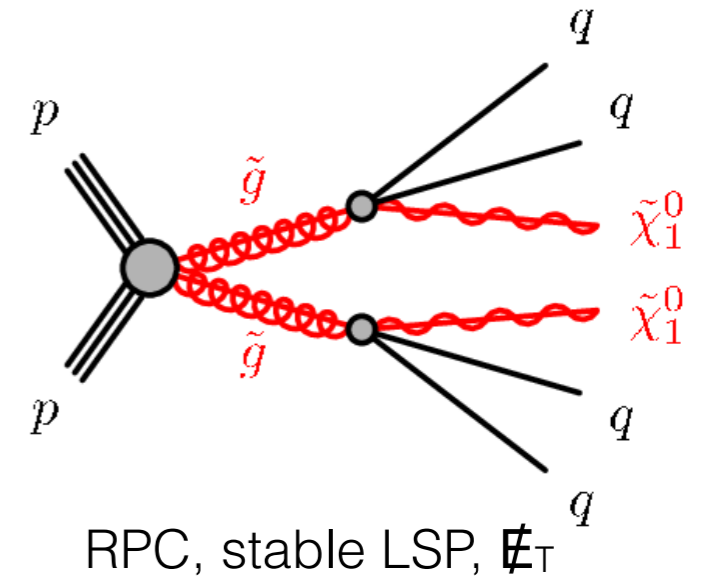
baryon violation

lepton violation
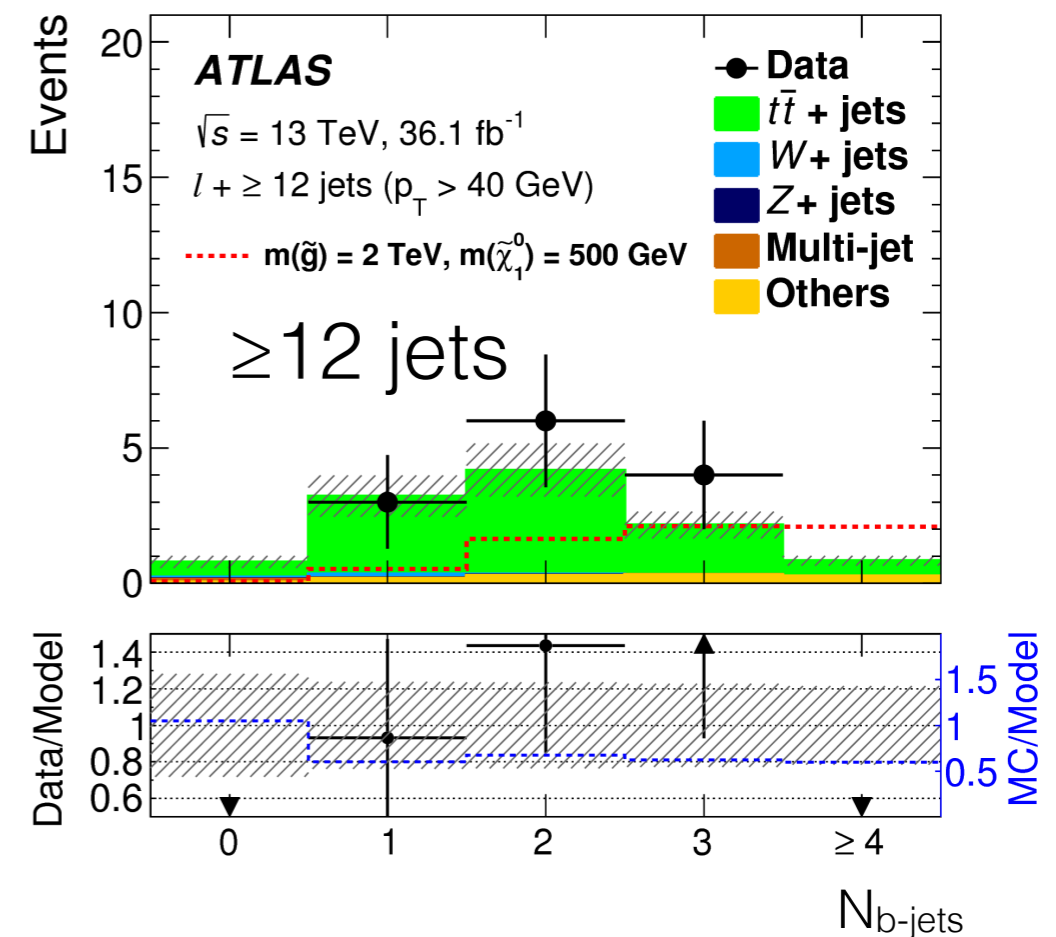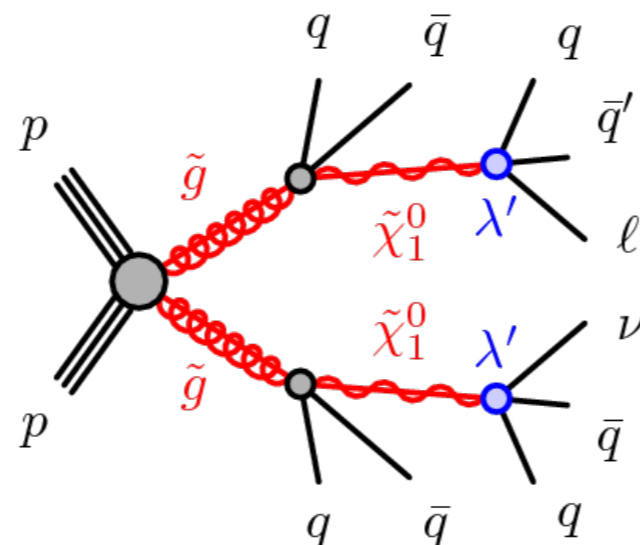
- LSP decays yield **high final state multiplicity**

- $\geq 1\ell$ + multi-jets, doesn't require $\not{E}_T$

- No significant excess

ATLAS

$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}

$l + \geq 12$ jets ($p_T > 40$ GeV)

$m(\tilde{g})$ = 2 TeV, $m(\tilde{\chi}_1^0)$ = 500 GeV

- Data
- $t\bar{t}$ + jets
- W+ jets
- Z+ jets
- Multi-jet
- Others

≥ 12 jets

$N_{b\text{-jets}}$

Search for paired resonances

- We can **fully reconstruct** SUSY particle mass

- Pair objects by minimizing angular separation.

- Veto events with large mass difference.

- Look for resonance peak in average mass.
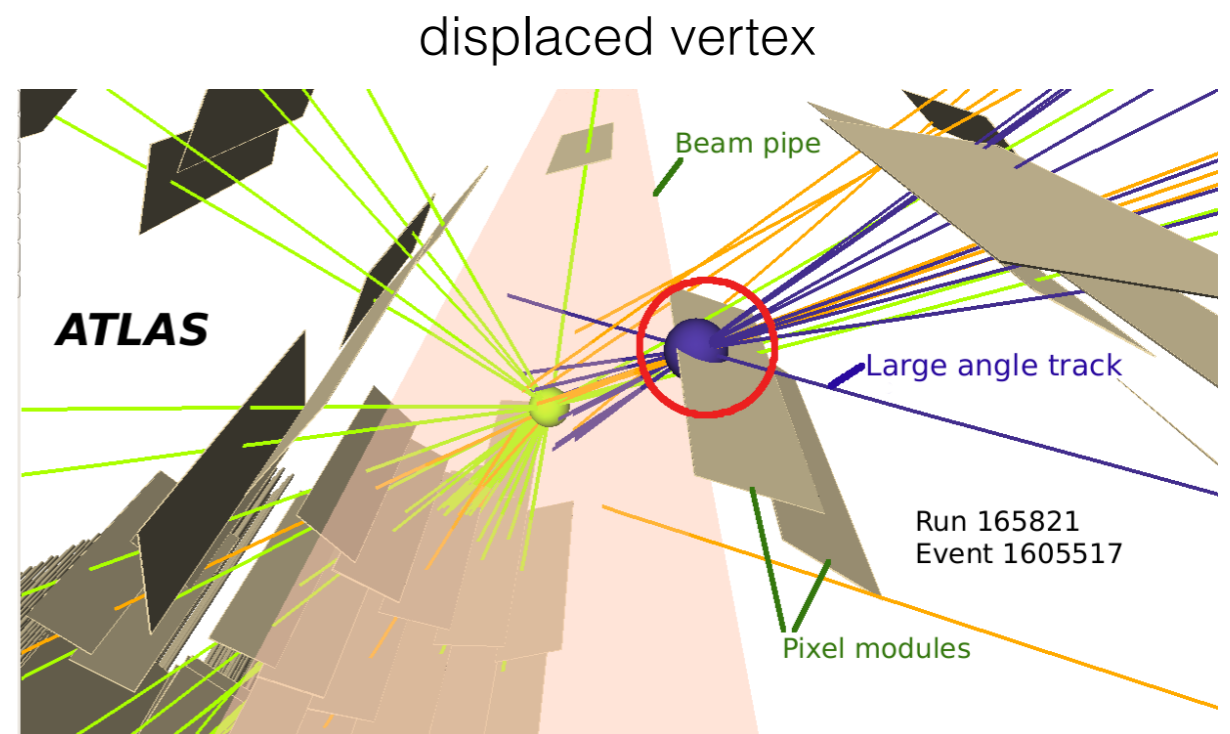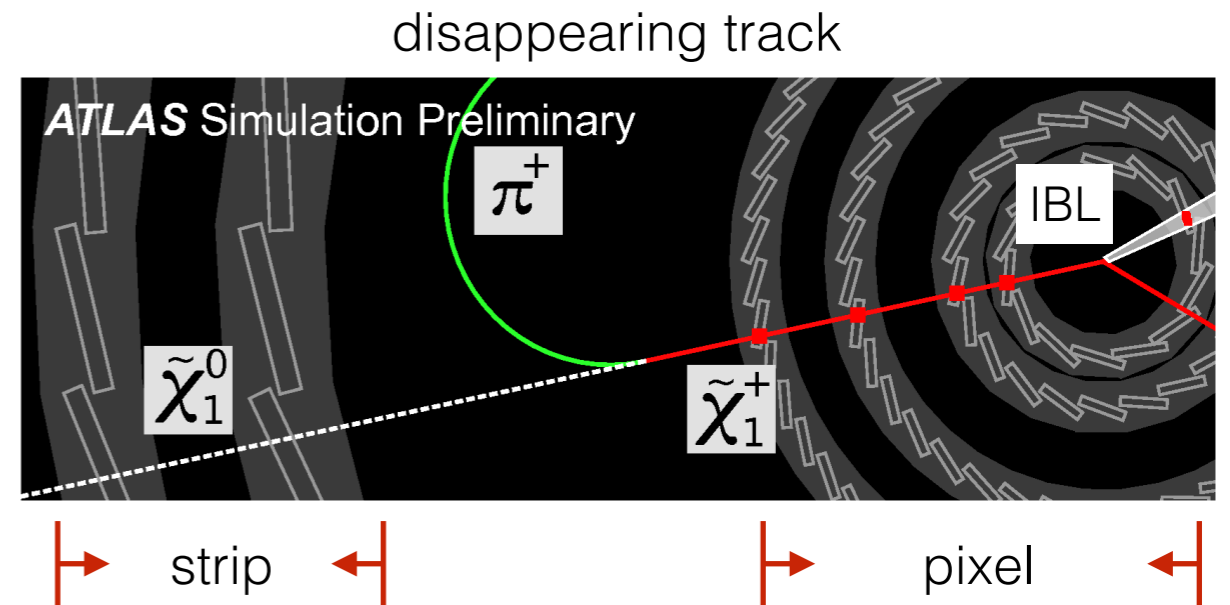
- No significant excess.
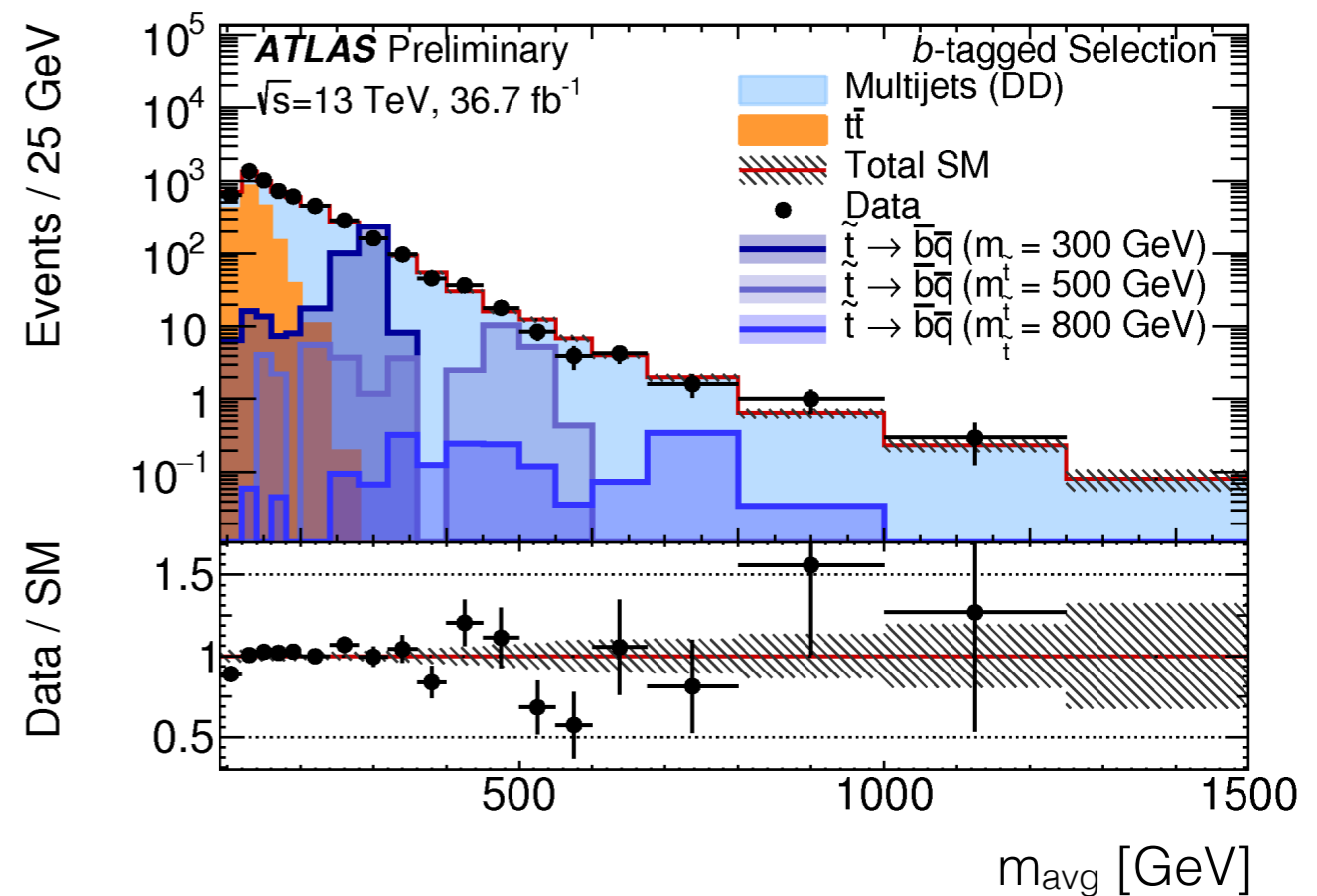
Results of RPV SUSY search

- No excess observed.

- High FS multiplicity analysis excludes gluino mass up to 2100 GeV.

- Paired resonance analysis excludes stop mass up to 600 GeV.

search with high FS multiplicity
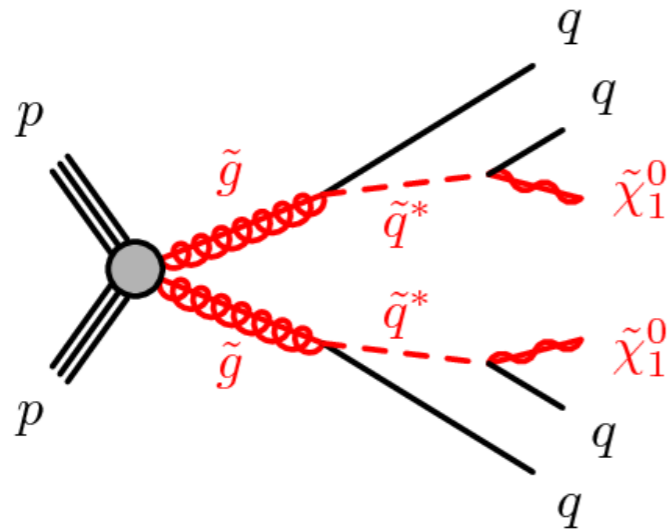

search for paired resonance
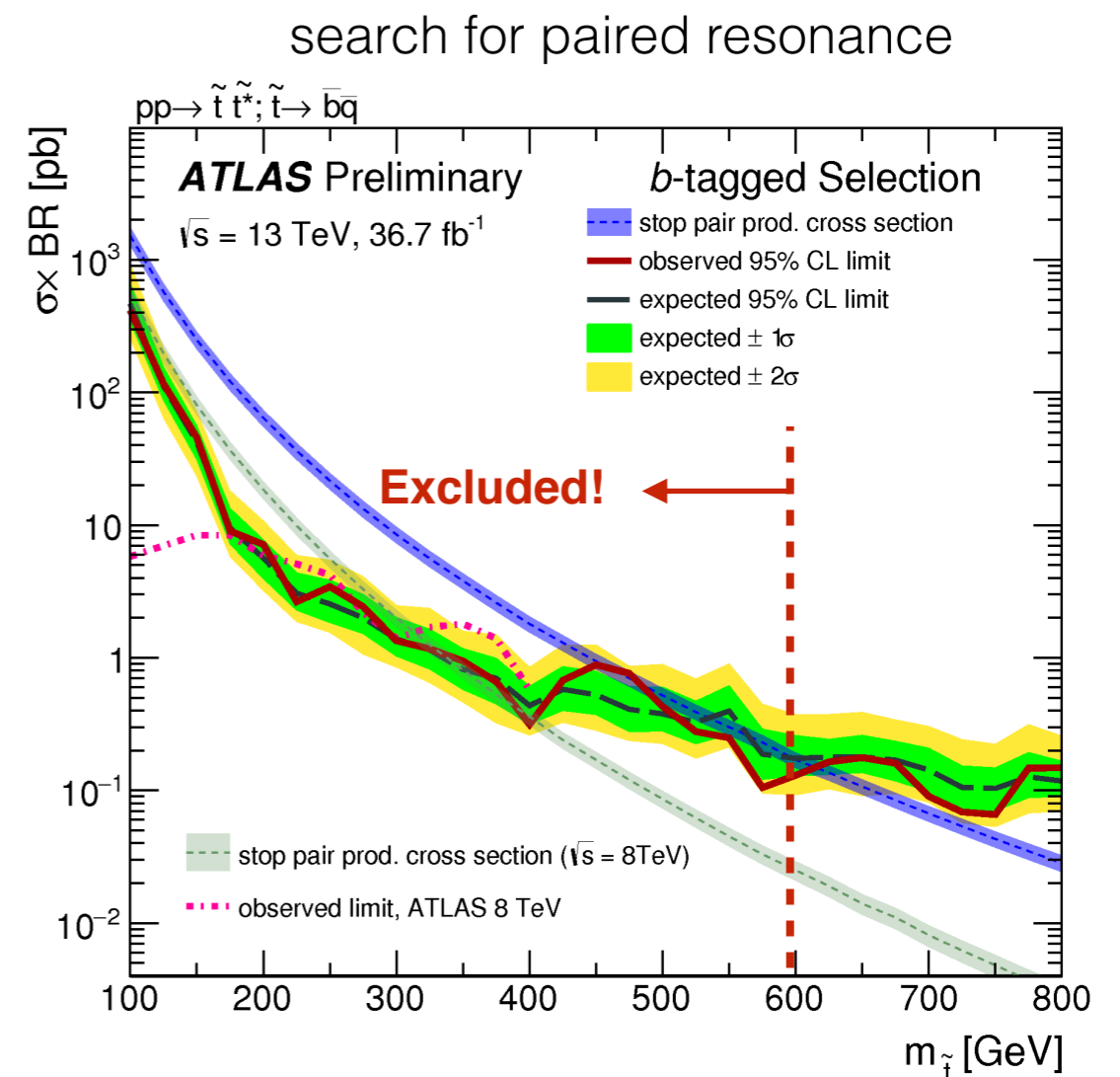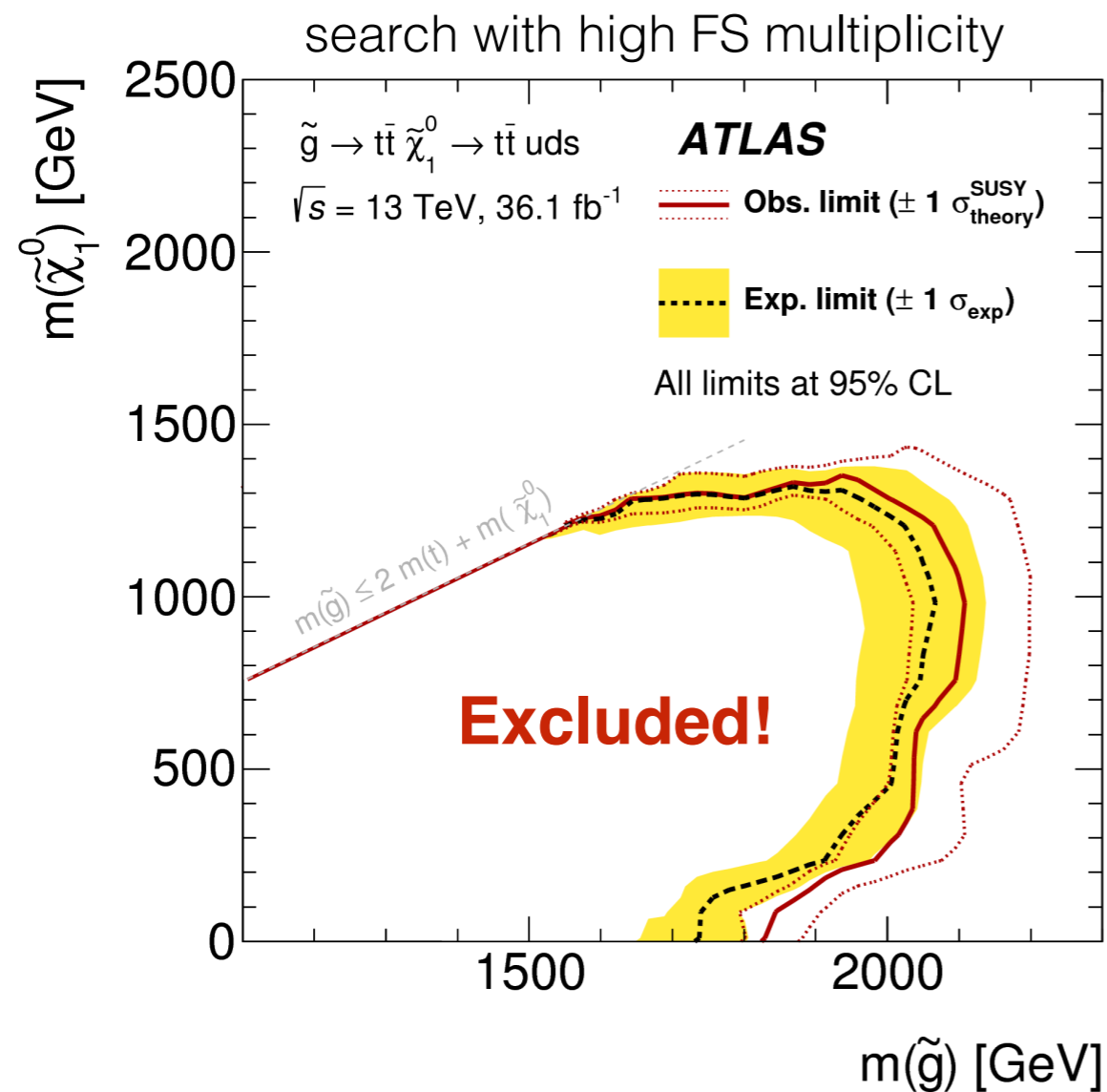
Search for long-lived particles

1. Another possibility why we haven't find SUSY is that they might have long lifetime and fly long distances before decaying

2. SUSY particles can have long lifetime if the mass splitting is small

   • look for disappearing tracks

3. or the virtual particle is too heavy
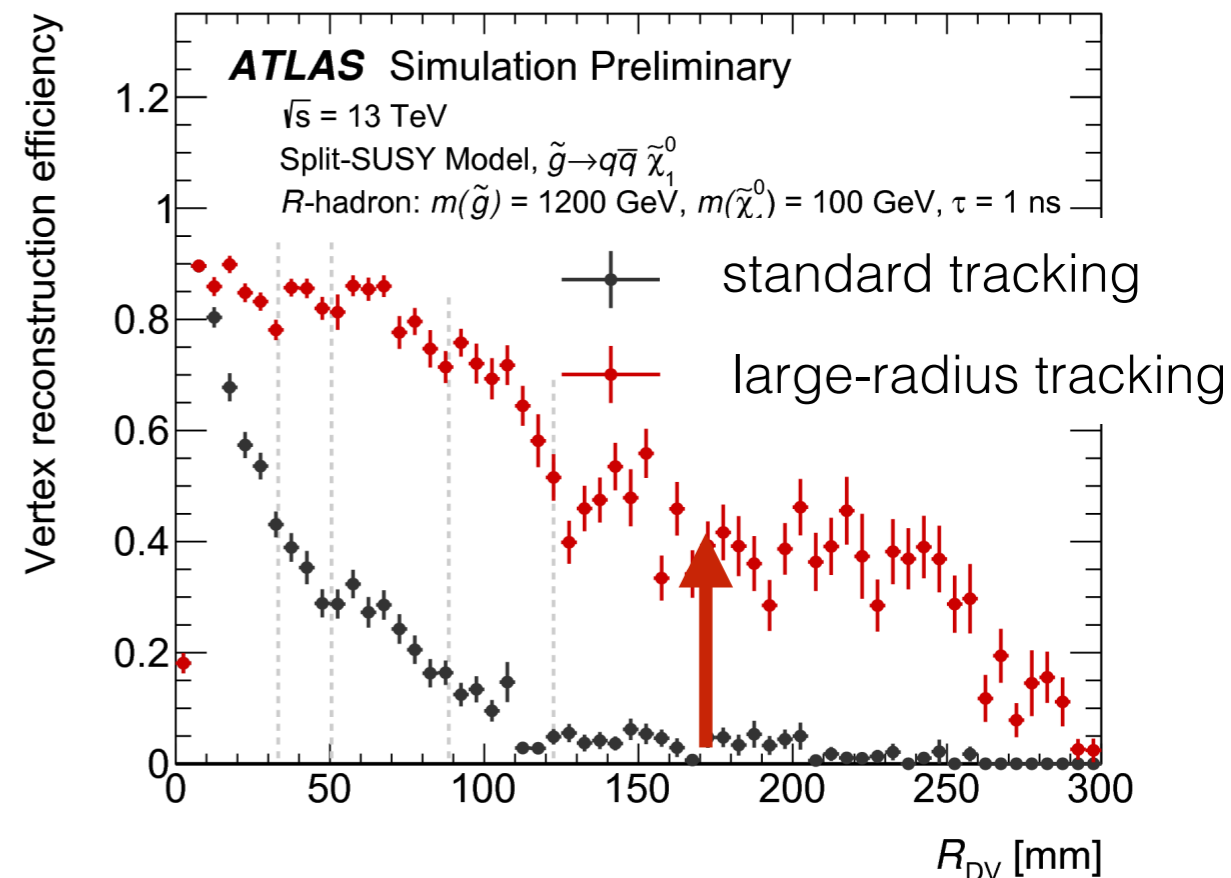
   • look for displaced vertices

disappearing track

ATLAS Simulation Preliminary

π^+

IBL

$\tilde{\chi}_1^0$ $\tilde{\chi}_1^+$

strip   pixel

displaced vertex

Beam pipe

ATLAS

Large angle track

Run 165821
Event 1605517

Pixel modules

Search for LLP with displaced vertices
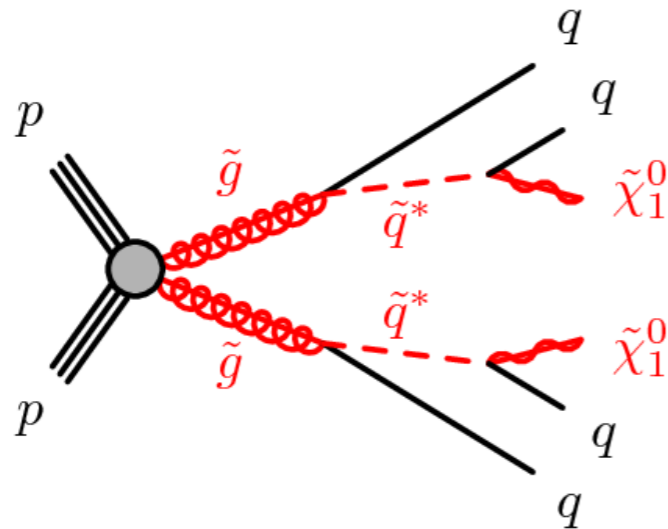
heavy virtual squark➞long lived gluino

- Look for displaced vertex (up to R=300 mm).

- Specialized **large-radius tracking**

  - $|d_0|$<300 mm (standard <10 mm)

  - $|z_0|$<1500 mm (standard <250 mm)
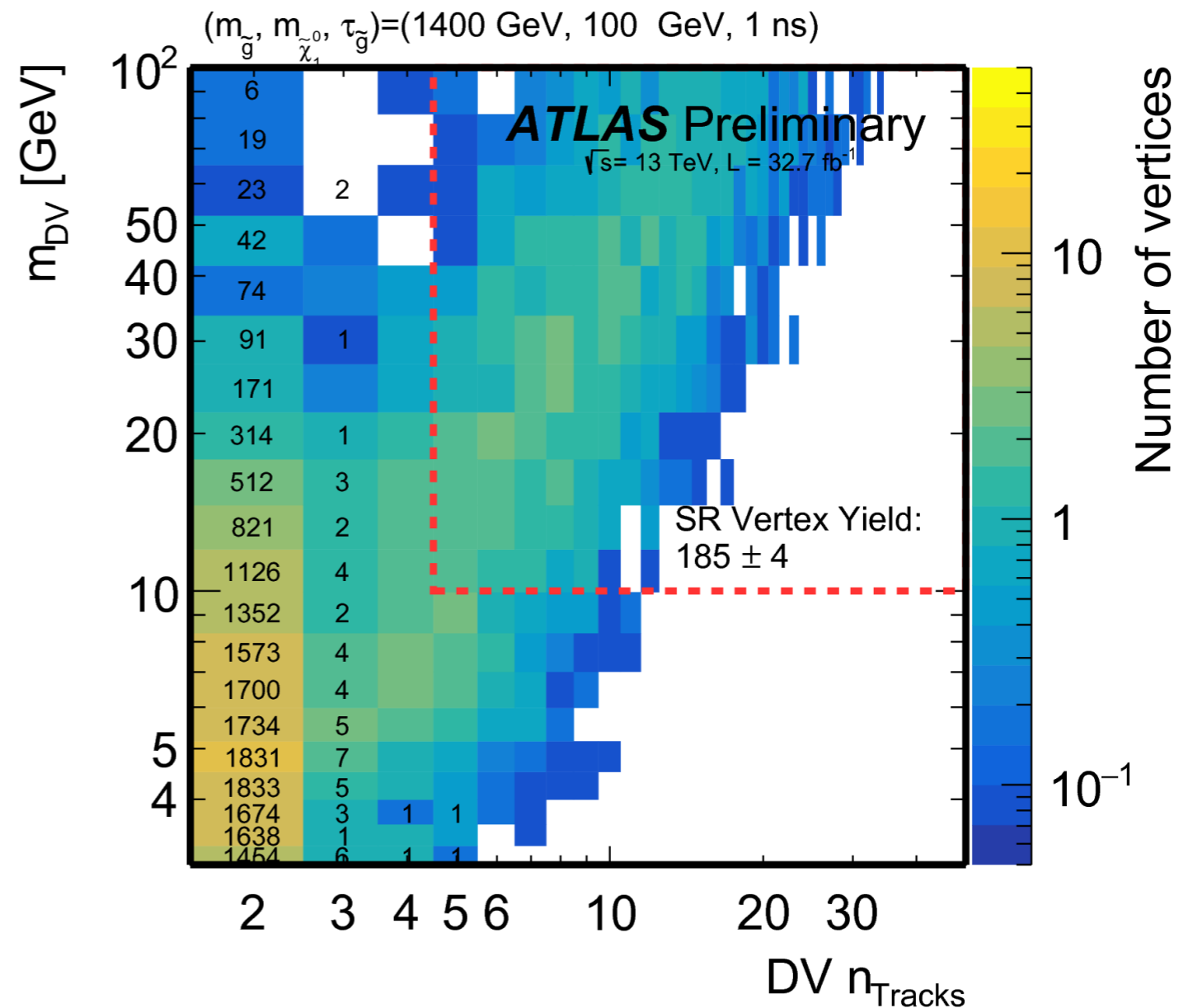
- Vertex reconstruction efficiency improves!

ATLAS Simulation Preliminary
$\sqrt{s}$ = 13 TeV
Split-SUSY Model, $\tilde{g} \rightarrow q\bar{q} \tilde{\chi}_1^0$
R-hadron: $m(\tilde{g})$ = 1200 GeV, $m(\tilde{\chi}_1^0)$ = 100 GeV, τ = 1 ns

standard tracking
large-radius tracking

Search for LLP with displaced vertices (cont.)

heavy virtual squark→long lived gluino

- Select events with

  - vertex mass **m_{DV}>10 GeV**

 - associated tracks **$n_{track}≥5$**.

- 0 events observed → No excess.

$(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}, \tau_{\tilde{g}}) = (1400 \text{ GeV}, 100 \text{ GeV}, 1 \text{ ns})$

ATLAS Preliminary
$\sqrt{s}$= 13 TeV, L = 32.7 fb^{-1}

SR Vertex Yield:
185 ± 4

color: signal model
number: data observation

Search for LLP with disappearing track

small Δm, χ±→LSP+very soft π±

disappearing track

strip   30 cm   12 cm   pixel
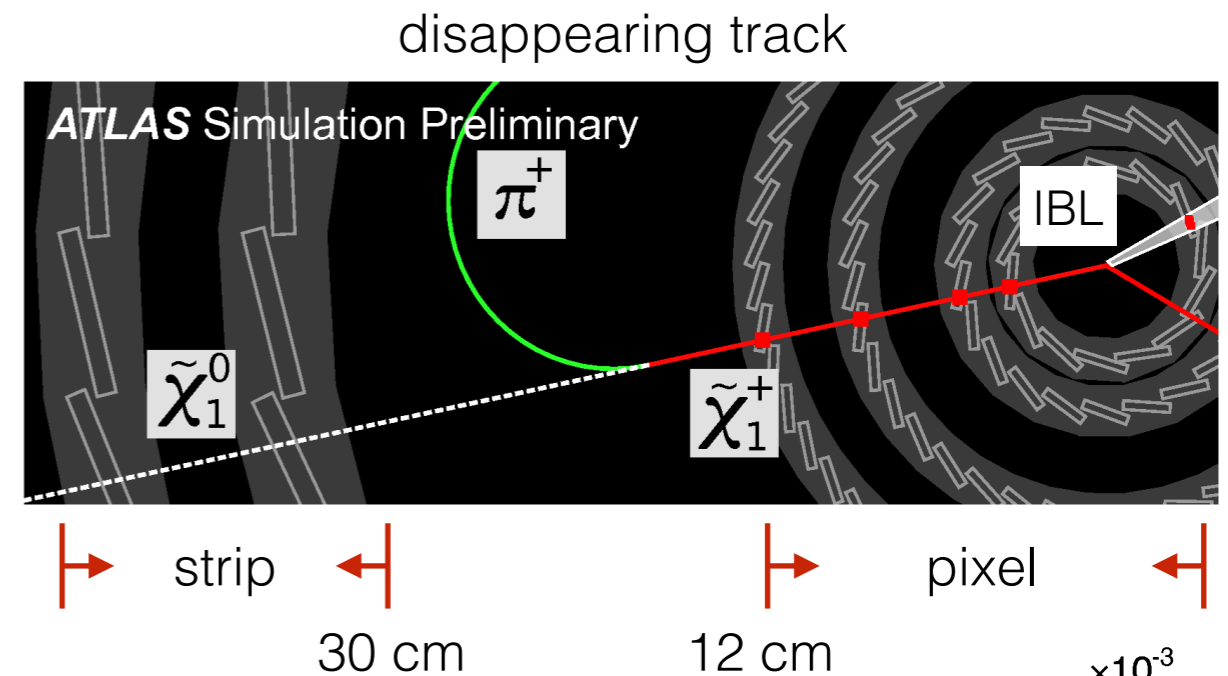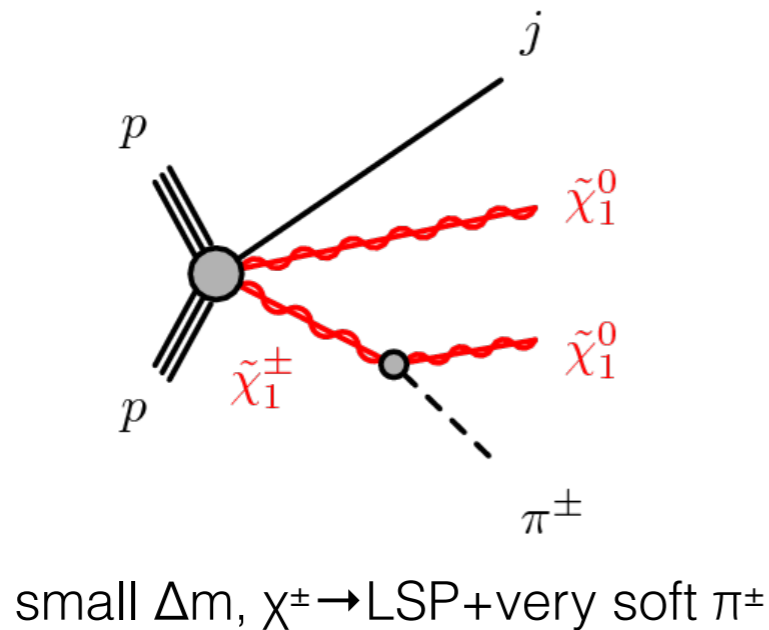
- Use pixel hits not associated to standard tracks to form **tracklets**.

- Zero strip hit associated to tracklet.

- Run1, 3 pixel+ 1 SCT layers (30 cm)

- Run2, with Insertable B-layer, 4 pixel layers (12 cm)
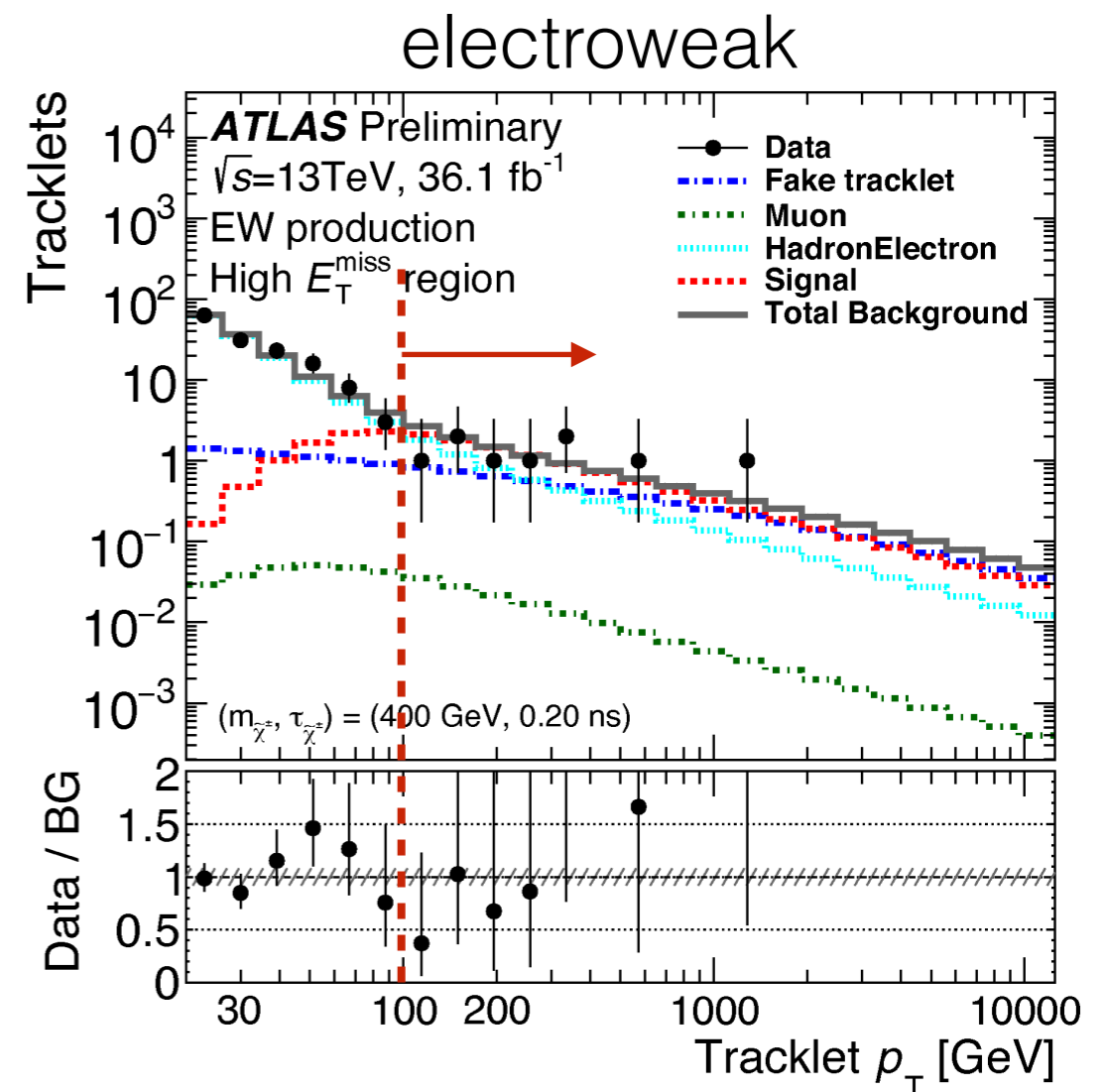
- Improve sensitivity from 1ns → 0.4ns
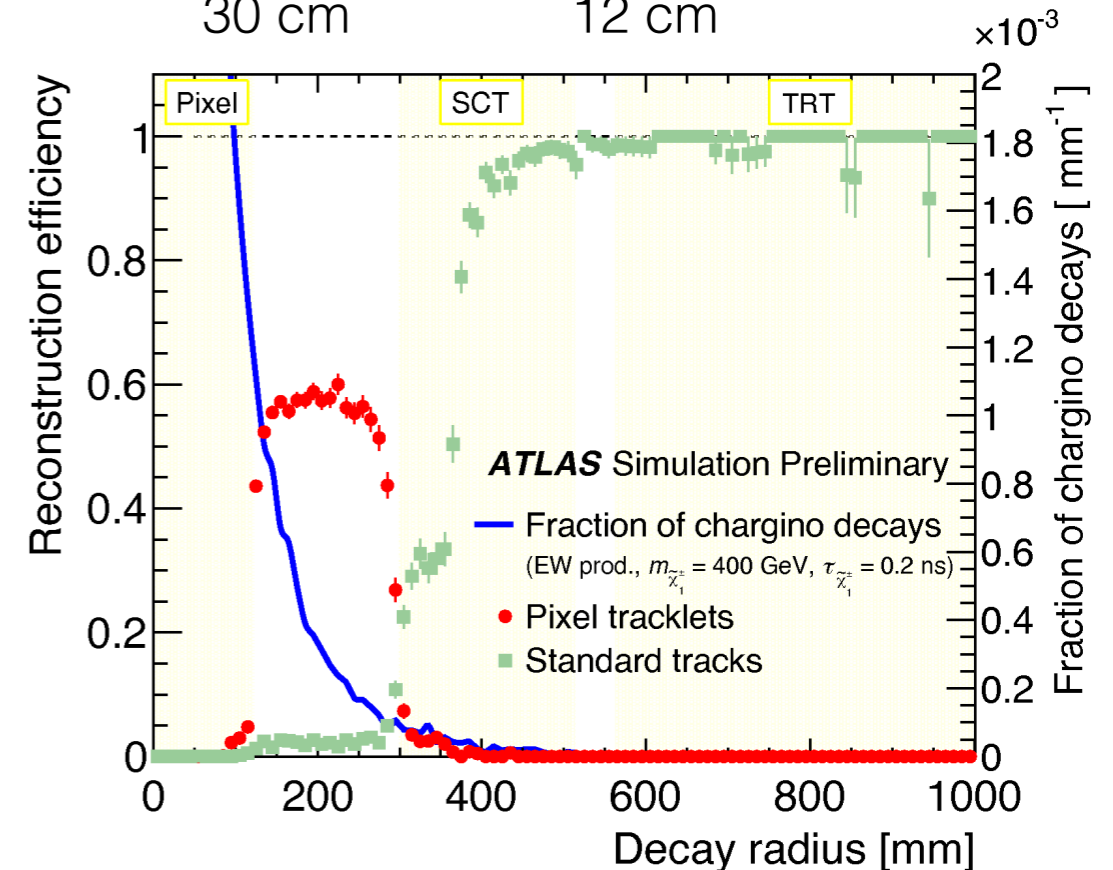
std. tracking has no sensitivity to long-lived chargino

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Search for LLP with disappearing track (cont.)

electroweak   strong

small Δm, χ± → LSP + very soft π±
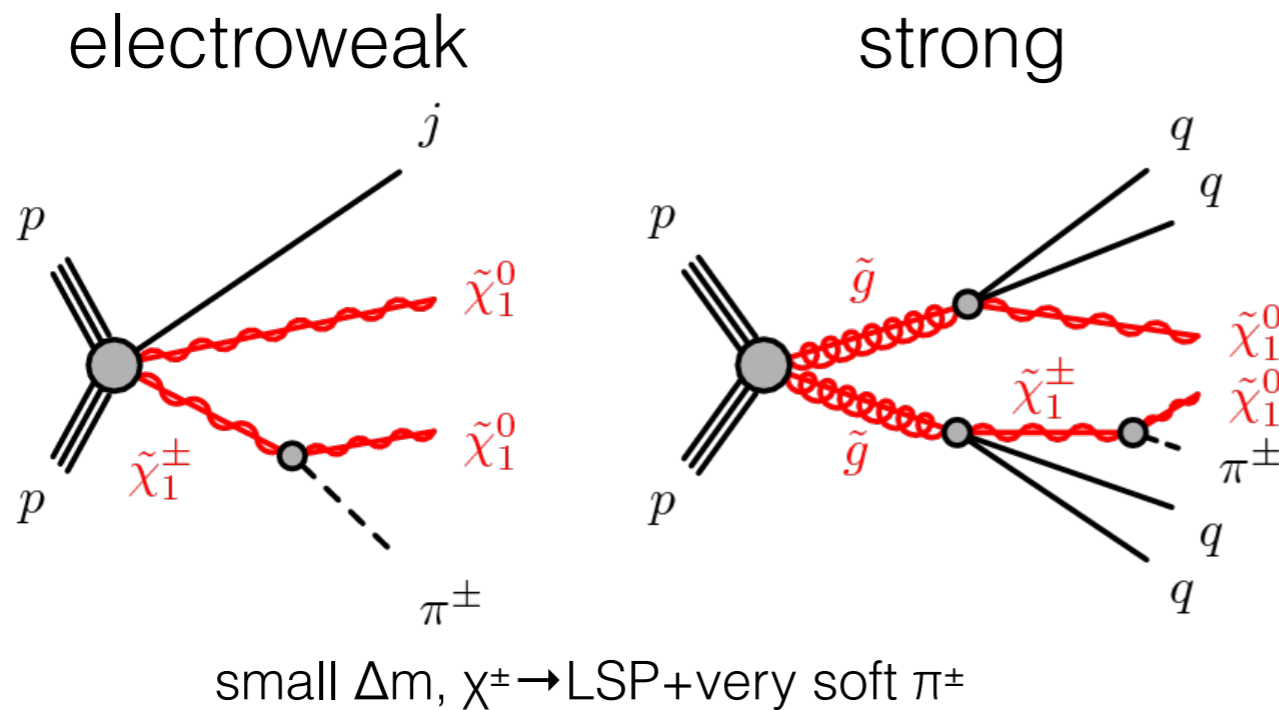
electroweak

- Soft objects do not fire triggers → $\not{E}_T$ trigger (threshold 70-100 GeV)

- Require

  - one ISR-jet for electroweak model

  - or on multi-jets for strong model.

- No significant excess.

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Results of LLP search

- In **displaced vertex** search gluino mass is excluded up to 2300 GeV.

- In **disappearing track** search chargino mass is excluded up to 550 GeV.

search with displaced vtx.

search with disappearing trk.
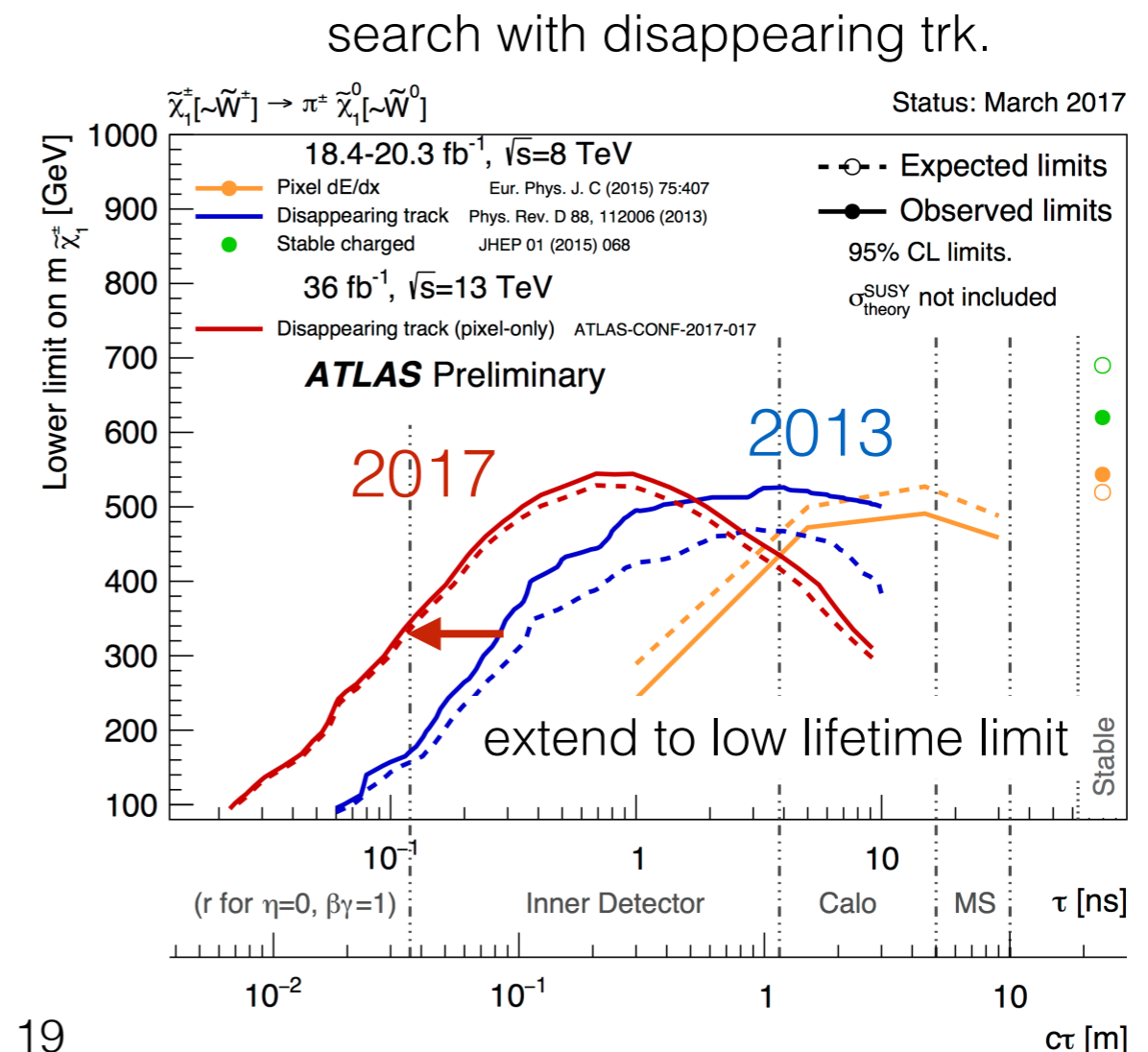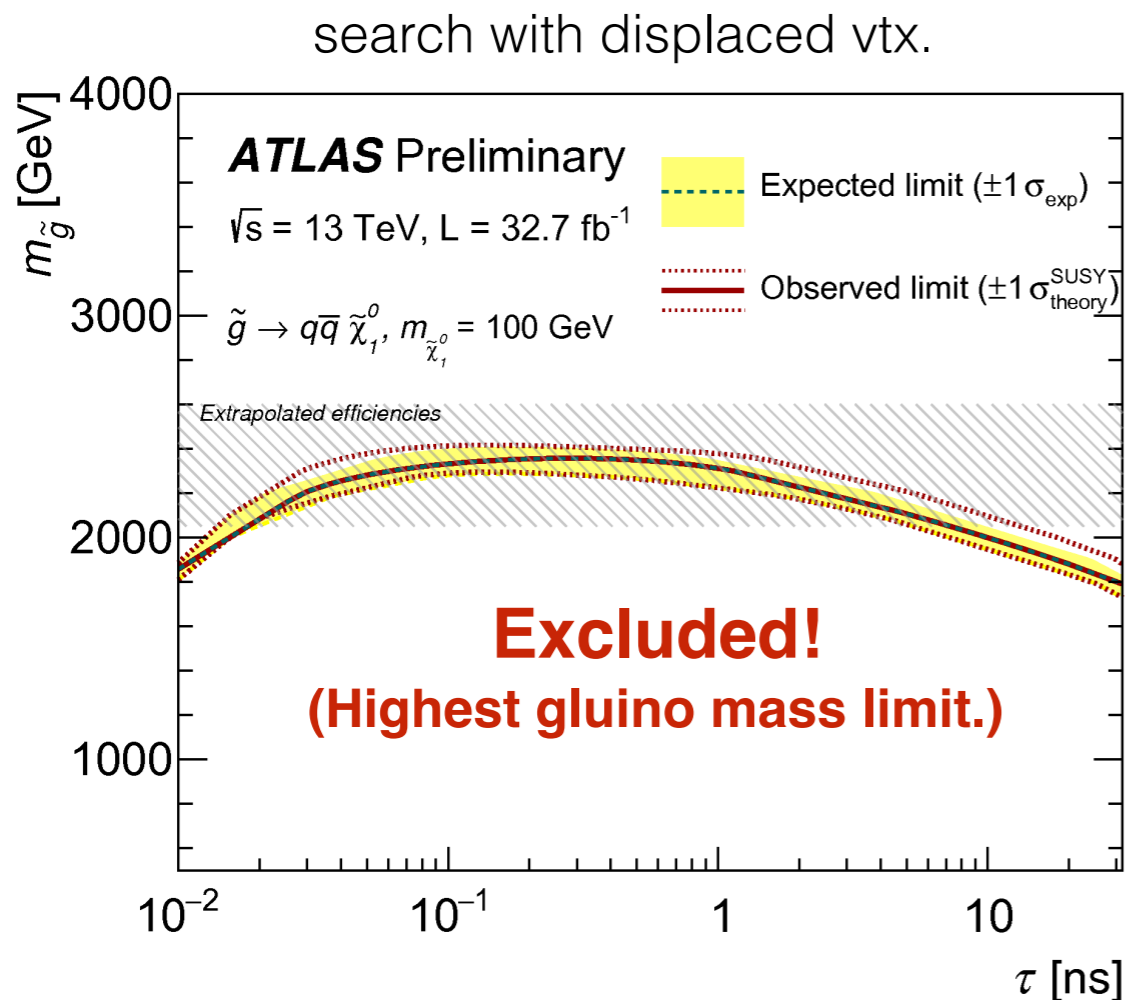
Summary

1. Conventional approach to search for gluino with multi-jets & $\not{E}_T$ excludes m[gluino] up to 2 TeV. No sign of SUSY.

2. We explore different approaches to look for EW gaugino, R-parity violating SUSY, and long-lived particles:

   - (multi-ℓ & $\not{E}_T$) probes **gaugino** mass up to 1 TeV.

   - (paired resonance) probes **stop** mass up to 2 TeV.

   - (displaced vtx & disappearing trk) probes **gluino** mass up to 2 TeV.

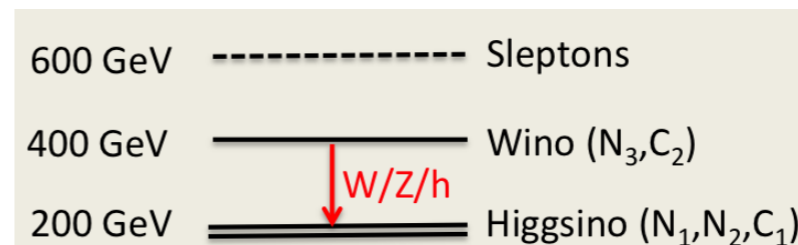3. Latest EW SUSY/LLP/RPV analyses using 2015+2016 13 TeV data still show no sign of SUSY.
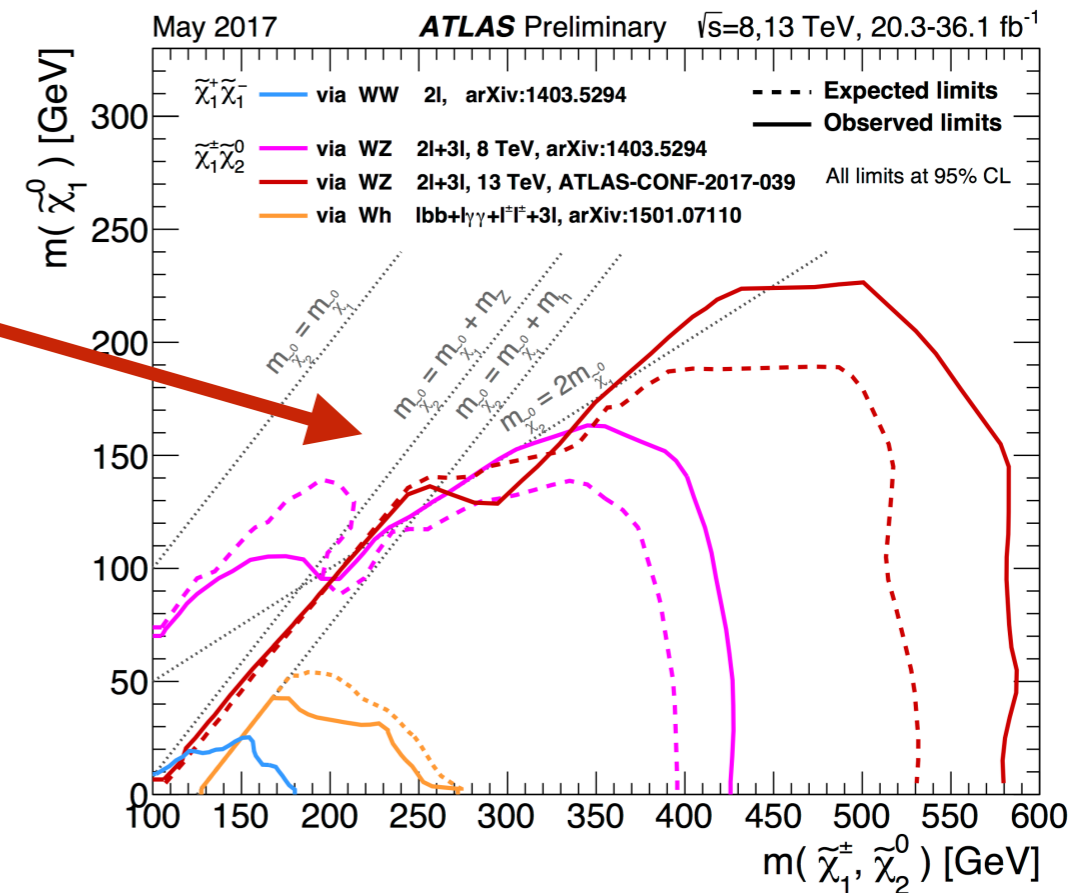
What are we still missing?

1. Here is one example: SUSY can still live in few hundred GeV range with **mass splitting < 100 GeV** (an unexplored phase space).
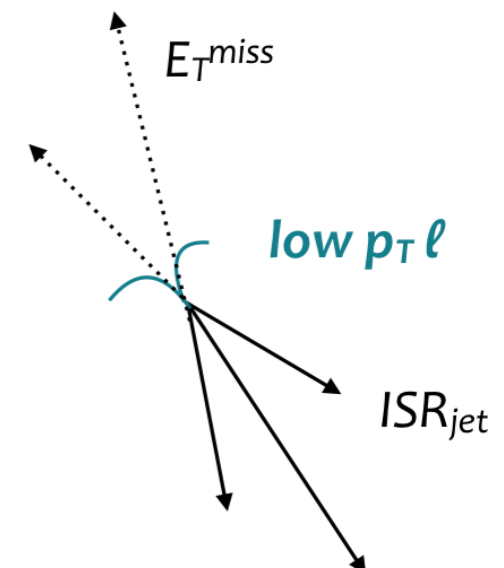
2. Search for Δm<100 GeV model is challenging

   - need to use soft objects (~few GeV)

   - signal v.s. background distributions are very similar.

   - use **advanced analysis techniques** (Super razor, Recursive Jigsaw…)

   - CMS has started probing compressed higgsino models with very nice results: http://cds.cern.ch/record/2256640?ln=en

3. There are many others possibilities to search for SUSY. Look forward to another ~100/fb over next two years allowing us to probe these possibilities.

photos from: https://particlebites.com/?p=4753

Thanks for listening

Reference

- Electroweak SUSY

  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-039/ATLAS-CONF-2017-039.pdf

  - https://cds.cern.ch/record/2265807/files/ATLAS-CONF-2017-035.pdf

- Long-lived particle

  - https://cds.cern.ch/record/2258161/files/ATLAS-CONF-2017-026.pdf

  - https://cds.cern.ch/record/2258131/files/ATLAS-CONF-2017-017.pdf

- R-parity violating SUSY

  - https://arxiv.org/pdf/1704.08493.pdf

  - https://cds.cern.ch/record/2265808/files/ATLAS-CONF-2017-036.pdf

  - https://cds.cern.ch/record/2258148/files/ATLAS-CONF-2017-025.pdf

Other useful links

- LHC seminar talks from Serhan and Moritz

  - https://indico.cern.ch/event/632395/

  - https://indico.cern.ch/event/580623/

- Moriond talks:

  - Cornering natural SUSY (Andreas) https://indico.in2p3.fr/event/13763/session/4/contribution/89/material/slides/0.pdf

  - The way forward (Lesya) https://indico.in2p3.fr/event/13763/session/4/contribution/90/material/slides/0.pdf

  - Squarks/gluinos (Emma) https://indico.in2p3.fr/event/13763/session/4/contribution/84/material/slides/0.pdf

  - Disappearing track (Toshiaki) https://indico.in2p3.fr/event/13763/session/7/contribution/75/material/slides/0.pdf

- Recent ATLAS SUSY results: https://www.dropbox.com/s/fv4utbwdy27j9y3/Hooberman_ANLWorkshop_v3.pdf?dl=0
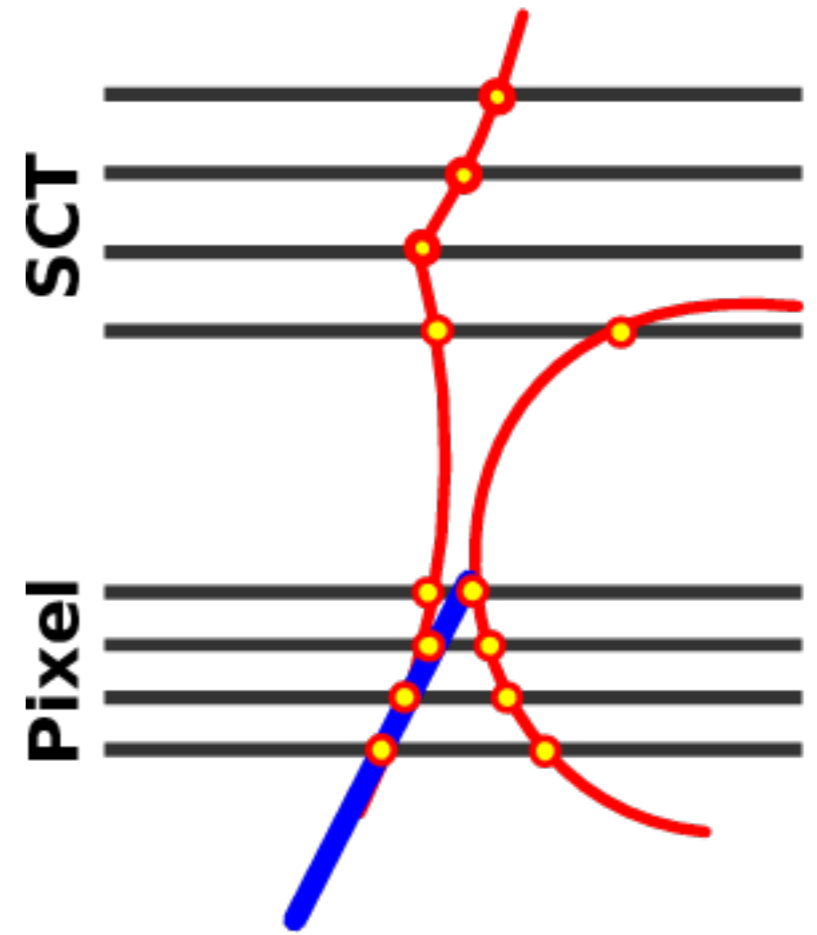
Backgrounds of disappearing tracks

Red solid: charged particle
Red dotted: neutral particle
Blue: tracklet
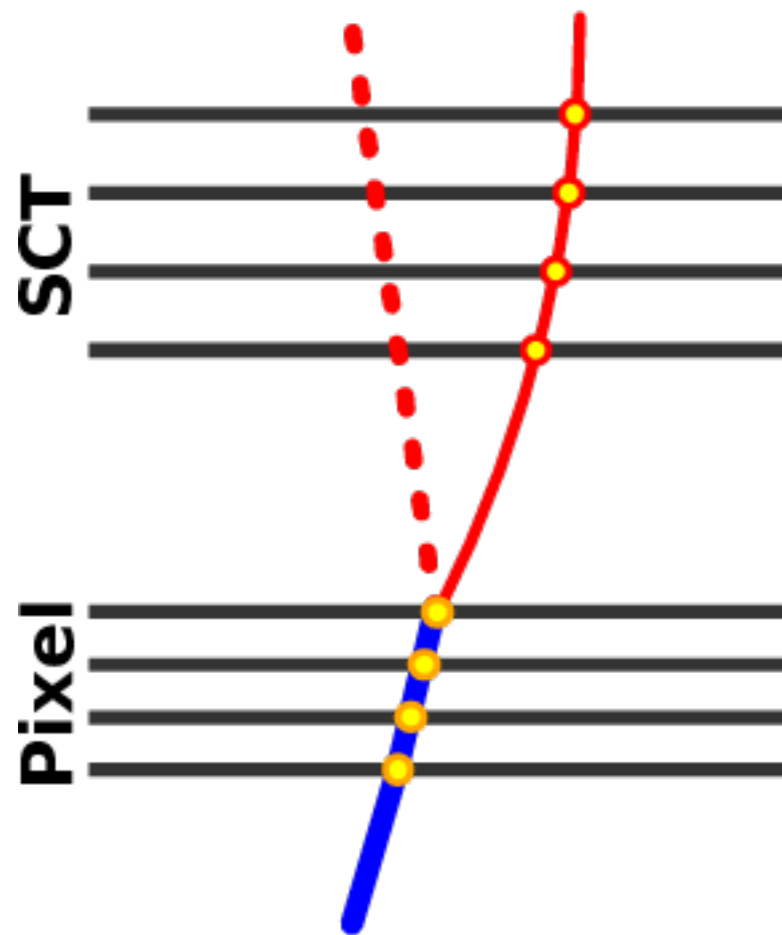
Hadron hard-scattering   lepton emitting photon   random combination of hits
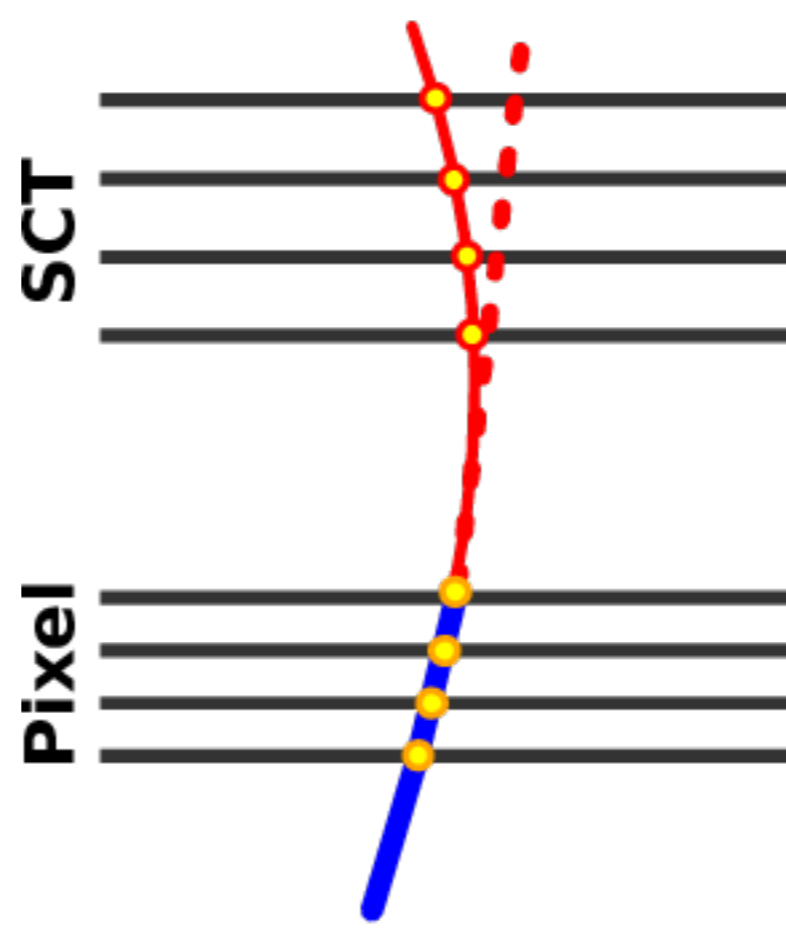
Background of displaced vertices

1. Residual hadronic material interactions

   - Extrapolate bkg template from low m_{DV} to high m_{DV} region.

2. Merged vertices

   - Build vertex separation function $d(V_1, V_2)$ by randomly merge vertices from distinct events.

3. Accidental crossing vertices and tracks

   - Add pseudo-track to n-track vertices to build n+1 track vertex template.